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CONTENTS

Pages

Geomorphology of Marguerite Bay area, Palmer Peninsula, Antarctica. By Robert L. Nichols 1421–1450

Pennsylvanian marine cyclothems in Tennessee. By Charles W. Wilson, Jr., and Richard G. Stearns 1451–1466

Petrology of several pegmatites in the Keystone district, Black Hills, South Dakota. By P. M. Orville 1467–1490

Correlation of the Cretaceous formations of the Pacific Coast (United States and northwestern Mexico). By W. P. Popenoe, R. W. Imlay, and M. A. Murphy 1491–1540

Short Notes

Subdivision of the Quaternary alluvium east of the Front Range near Denver, Colorado. By Glenn R. Scott 1541–1544

Slips and separations. By Vincent C. Kelley 1545–1546

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PAPERS IN PRESS FOR FORTHCOMING ISSUES

UPPER DEVONIAN CORRELATIONS IN WESTERN UTAH AND EASTERN NEVADA. By David L. Clark and Joseph H. Becker

STRATIGRAPHY AND PALEONTOLOGY OF A LATE PLEISTOCENE BASIN, HARPER COUNTY, OKLAHOMA. By John J. Stephens

SUBGLACIAL, MARGINAL, AND OTHER GLACIAL DRAINAGE IN THE SYRACUSE-ONEIDA AREA, NEW YORK. By J. B. Sissons

PETROLOGY OF BASALTIC ROCKS IN PART OF THE LABRADOR TROUGH. By W. Robert A. Baragar

POST-PLIOCENE UPLIFT OF THE SIERRA NEVADA, CALIFORNIA. By F. S. Hudson

EVOLUTION OF TILL-STONE SHAPES, CENTRAL NEW YORK. By Chauncey D. Holmes

ANORTHOSITE-ADAMELLITE COMPLEX OF NAIN, LABRADOR. By E. P. Wheeler, 2nd

BERMUDA: A PARTIALLY DROWNED, LATE MATURE, PLEISTOCENE KARST. By J Harlen Bretz

PETROGENESIS OF BALD ROCK BATHOLITH, CALIFORNIA: A NEW PETROGRAPHIC STUDY: By Leonard H. Larsen and Arie Poldervaart

Editor's Note: Separate copies of *Correlation of cretaceous formations of the Pacific Coast* (*Chart 10e*), printed in this issue, are available at 50 cents per copy.

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82. OLIGOCENE PLANTS FROM THE UPPER RUBY BASIN, SOUTHWESTERN MONTANA. By Herman F. Becker

Description of a well-preserved flora (37 families, 61 genera, and 82 identifiable species, 25 of which are new) from Tertiary fossiliferous shales of the Ruby Basin. The author uses the flora to interpret the paleoecology and paleoclimatology and suggests that the Ruby and Florissant assemblages represent a single botanical province.

About 100 pages, 4 figures, 32 photographic plates
Expected date of issue, November

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 71, PP. 1421–1450, 17 FIGS., 4 PLS. OCTOBER 1960

GEOMORPHOLOGY OF MARGUERITE BAY AREA, PALMER PENINSULA, ANTARCTICA

By Robert L. Nichols

Abstract

A snow-covered plateau hundreds of miles long extends from the northern to the southern part of the Palmer Peninsula, Antarctica. It is approximately 2000 feet high at the northern end and more than 6000 feet high at the southern end. The plateau presumably is a middle or late Tertiary peneplain which has been differentially uplifted. The peneplain was dissected after the uplift; depression of more than 1000 feet since then has resulted in a shore line of submergence.

Wright, Priestley, and Gould thought that glaciation started in the Antarctic in the middle Tertiary because they interpreted breccias as tillites. The writer concludes after an examination of the literature that these breccias are probably volcanic; he believes that there is no good evidence for Tertiary Antarctic glaciation.

U-shaped valleys, cirques, horns, truncated spurs, arêtes, glacially formed bedrock basins, erratics, and moraine are common.

Evidence of deglaciation is widespread. Land ice extended more than 15 miles beyond the present strand line during the most advanced stage of glaciation. Three thousand feet of ice covered areas now deglaciated. The southwest terminus of the shelf ice in King George VI Sound retreated approximately 30 miles from 1940 to 1949. The Northeast Glacier retreated measurably from 1940 to 1947.

A strand flat 1500 feet long, 400 feet wide, and in places as much as 20 feet above sea level was mapped. Till buried in places by elevated beach gravels veneers its bedrock platform. The strand flat was formed by a local glacier. Since its formation, sea level has dropped as much as 20 feet with respect to the land. Other strand flats have had a somewhat similar history.

More than 20 elevated beaches were studied. The highest is approximately 110 feet above sea level. Elevated beaches have also been reported from South Victoria Land and from the northern part of the Palmer Peninsula. The elevations of these beaches suggest that on the average more than 300 feet of ice has been removed from the margin of the continent during deglaciation.

The average depth of the break in the slope of the Antarctic continental terrace is approximately 1600 feet. The world average depth of the break in slope is approximately 430 feet. If the great depth of the Antarctic break in slope is due solely to the weight of the icecap, the icecap must average between 3550 and 4800 feet thick.

More than 75 per cent of the area is covered with permanent ice. Valley, piedmont, tidewater, cliff, cirque, reconstructed, outlet, transection, and fringing glaciers are common; so too are highland, snowdrift, shelf, and island ice.

The insignificant quantity of alluvium and the small size of the meltwater streams in the summer months prove that running water is of only minor importance as a geologic agent.

CONTENTS

TEXT

	Page
Introduction	1422
Description of area	1422
Peneplain	1423
Shore line of submergence	1426
Pre-Pleistocene Antarctic glaciation	1426
Glacial features	1428
Deglaciation	1428
Strand flats	1431
Weathering	1433
Elevated beaches	1434
Talus	1438
Block terraces	1438
Alluvium	1440
Average thickness of Antarctic continental icecap	1440
Glaciers	1442
Cliff and snout termini	1445
Bay ice	1447
Squeeze-ups	1447
Ponds	1447
Slush	1448
References cited	1449

ILLUSTRATIONS

Figure		Page
1.	Map of Antarctica showing location of the Palmer Peninsula	1423
2.	Index map	1424
3.	Map showing the localities studied in the Marguerite Bay area, Antarctica	1425
4.	U. S. Navy Department, Hydrographic Office Chart No. 5411	1427
5.	Former extension of the ice at Terra Firma Islands, Antarctica	1430
6.	Upper limit of glaciation at Roman Four Mountain, Antarctica	1430
7.	Geologic map of the strand flat near Neny Fjord Thumb (unofficial name), Antarctica	1432
8.	Cross section of strand flat	1433
9.	Alluvium deposited on talus slope	1438
10.	Field sketches of block terrace	1439
11.	Diagrammatic sketches showing the formation of block terraces	1441
12.	Brash and growler ice field next to Northeast Glacier, Antarctica	1443
13.	Snowdrift ice slab on the east side of Stonington Island, Antarctica	1445
14.	Snout terminus south of Red Rock Ridge, Antarctica	1446
15.	Snout terminus of the Northeast Glacier, Antarctica	1446
16.	Squeeze-ups found on bay ice	1447
17.	Formation of synclinal fresh-water ponds and slushy snow on bay ice	1448

Plate		Following page
1.	Aerial photographs of the Northeast and Neny glaciers, Antarctica	1434
2.	Antarctic glaciers	1434
3.	Strand-flat and elevated beaches, Antarctica	1434
4.	Examples of weathering, block terraces brash and growler ice field, snowdrift ice slabs, and synclinal ponds, Antarctica	1434

TABLES

Table		Page
1.	Elevated beaches of Marguerite Bay, Palmer Peninsula, Antarctica	1436
2.	Antarctic elevated beaches, marine caves, marine terraces	1437

Introduction

From March 1947 to March 1948 the writer, while a member of the Ronne Antarctic Research Expedition, spent approximately 54 9-hour days in geologic field study of Marguerite Bay, Palmer Peninsula, Antarctica (Figs. 1, 2, 3). To accomplish this, the writer was on the trail for approximately 150 days and was a member of the expedition for about 470 days.

Participation on the expedition was made possible by a generous grant from The Penrose Bequest of The Geological Society of America and leave of absence given by Tufts College.

Warm-hearted thanks must be given to Mr. Robert H. T. Dodson, who was the writer's sole companion on a 90-day sledge trip, one of his companions on a 30-day sledge trip, and who worked with the writer on many local outcrops. He collected and labeled geologic specimens, made difficult and dangerous traverses and climbs to get geologic data, and in many discussions helped the writer crystallize his ideas on the geology of the area.

Special mention should also be made of Mr. William R. Latady, who also spent many days with the writer on the trail. Mr. Latady, the expedition photographer, took all the aerial photographs.

The Faulkland Islands Dependencies Survey loaned Figure 2 of Plate 2 to the writer. Prof. Marland P. Billings and Dr. Lawrence E. Nielsen have discussed several of the problems with the writer, and Profs. Robert P. Sharp and Charles E. Stearns critically read the manuscript and made many valuable suggestions.

The writer takes great satisfaction in acknowledging Captain Finn Ronne's keen interest in the geologic program, his understanding of the importance of the work, and his many personal kindnesses.

Description of Area

The Palmer Peninsula (Graham Land) runs nearly north and south and is the northernmost part of the Antarctic Continent (Fig. 1). The Drake Passage, approximately 600 miles wide (Fig. 2), separates it from the southern tip of South America. It joins Edith Ronne Land to the east and the Robert English Coast to the west, both of which are on the main part of the continent (U. S. Navy Dept. Hydrog. office, 1943b; Ronne, 1948, Fig. 1). The coast on both sides of the peninsula is characterized by indentations, inlets, bays, and fjords and by islands and bold headlands. A large percentage of the peninsula is covered with highland ice and snowdrift ice slabs, with valley, piedmont, tide-water, cliff, cirque, outlet, and fringing glaciers, and with extensive areas of shelf ice on both the east and west coasts. A good description and excellent photographs of the area were published by the U. S. Navy Department Hydrographic Office (1943a, p. 109–169).

Marguerite Bay is on the southwestern part of the peninsula (Figs. 2, 3).

PENEPLAIN

The summit of the Palmer Peninsula is a snow-covered plateau. It is about 2000 feet high in the northern part of the peninsula. It gradually increases in altitude southward and in the southern part reaches a height of 6000 or more feet (U. S. Navy Dept. Hydrog. Office, 1943a, p. 109). The plateau is 6000–8000 feet high between 66°30′S. and 68°00′S. (Fig. 4), approximately 6000 feet high between 65°30′S. and 66°30′S., 4000–6000 feet high at 64°00′S., and 2000 feet high from 64°00′S. northward (Army Air Forces Aeronautical Chart Service, 1949; 1950). Bedrock crops out near the summit of the plateau around the top of Richthofen Valley (between 65°30′S. and 66°00′S.), and three bedrock mountains project above the plateau between 63°10′S. and 63°30′S. The Directorate Colonial Surveys (1948) chart shows a very flat area at about 5000 feet between 67°30′S. and 68°00′S. and a plateau above 6000 feet between 66°00′S. and 66°30′S. Bedrock is shown not far below the summit of the plateau in both areas.

The plateau is present east of Stonington Island (Nichols, 1947b; 1948a, p. 3–4; 1953, p. 7–14) and is well developed immediately north and south of the terminus of Neny Glacier (Dorsey, 1945, Figs. 1, 2). Its distribution in this area is shown on a map made from a survey by A. Stephenson (Rymill, 1938, p. 432; *See also* p. 400). Two remnants of the plateau are located between Cape Berteaux and Windy Valley, and another is southwest of Black Thumb Mountain (Debenham, 1937, p. 253); an extensive flat remnant is found near Mount Edgell (Fig. 3). In the vicinity of Stonington Island an area of peaks, ridges, promontories, and valleys between the plateau and the coast, decreasing in altitude westward, probably has resulted from the dissection and erosion of the plateau. The plateau is, therefore, hundreds of miles long; where greatly dissected it is only a few miles wide, and in other places it is scores of miles wide.

Kevin Walton of the Falkland Islands Dependencies Survey and Arthur Owen of the Ronne Antarctic Research Expedition who

FIGURE 1.—MAP OF ANTARCTICA SHOWING LOCATION OF THE PALMER PENINSULA

have sledged on the plateau east of Stonington Island report (Personal communications) it is very flat with an occasional domal mountain rising 300–400 feet above it. This smoothness is due in part to the highland icecap which covers the plateau. Mount Edgell is a domal mountain which rises 1800 feet above the plateau remnants which surround it; peaks to the south rise even higher.

E. W. Bingham and A. W. Reece of the Falkland Islands Dependencies Survey have done considerable sledging on the plateau and report that they saw no outcrops on it. The absence of outcrops is also due to the highland icecap. In the northern part of the Palmer Peninsula from 63°00′S. to 66°00′S. the plateau, according to Andersson (1906, p. 23–31, Pl. 5), cuts folded Jurassic graywacke, slate, volcanic tuff, granite, quartz diorite, and gabbro. Immediately north of the terminus of Neny Glacier the plateau cuts pink granite and gabbro, and east of Stonington Island, Knowles (1945b, Map 1) found plutonic igneous rocks on the plateau. It seems likely that elsewhere in the Marguerite Bay area the plateau may also cut schist, gneiss, and argillite, a younger group of related intrusive bodies including gabbro, diorite, and granite, and a still younger series of volcanic tuffs, breccias, and agglomerates together with a red vuggy granite which intrudes them, as all of these are cut by surfaces younger than the plateau in the coastal area west of the plateau (Nichols, 1948a, p. 1–3). Where it has been studied, and probably everywhere else, the plateau is therefore an erosion surface (Howard, 1950, p. 1472–1473).

The group of related intrusive bodies which includes gabbro, diorite, granite, and other rock types is probably post–Juro-Cretaceous, as the granite cuts argillites which are probably of this age (Nichols, 1948a, p. 3). Correlation with similar rock types in South America indicates that they are probably Cretaceous (Geol. Soc. America, 1950). Neither the volcanic series nor the younger granite can be dated precisely. The younger granite is cut by trap dikes which may correlate with the Miocene basaltic volcanic rocks in the northern

FIGURE 2.—INDEX MAP

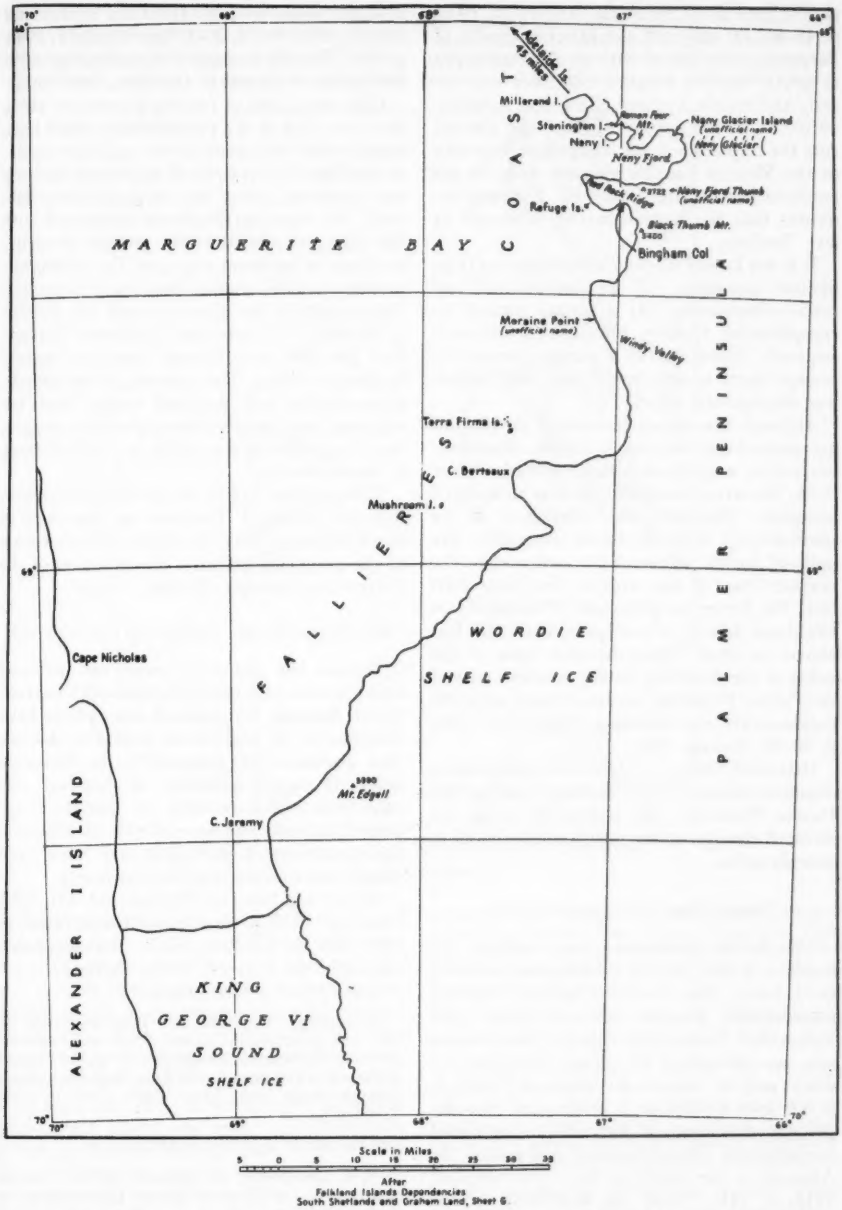

FIGURE 3.—MAP SHOWING THE LOCALITIES STUDIED IN THE MARGUERITE BAY AREA, ANTARCTICA

part of the Palmer Peninsula (Andersson, 1906, p. 45–50, 70) and with the Miocene basalts of Patagonia. Correlation with similar rock types in South America suggests that they may be early and middle Tertiary (Geol. Soc. America, 1950). It is not known whether the plateau cuts the trap dikes in the Marguerite Bay area or the Miocene basaltic volcanic rocks in the northern part of the Peninsula. Evidence indicates that the plateau surface is middle or late Tertiary.

It is not known whether the plateau is (1) an uplifted peneplain, (2) an uplifted plain of marine denudation, (3) a surface formed by cryoplanation (Peltier, 1950) which was subsequently tilted, or (4) a surface formed by erosion down to tree line (Daly, 1905) which was subsequently tilted.

Although the surface features of the plateau are masked and bedrock is almost completely covered by a highland icecap hundreds of feet thick, the writer assumes that it is an uplifted peneplain. The uplift was differential: in the southern part of the peninsula the surface was uplifted several thousand feet, whereas in the northern part it was uplifted less than 2000 feet. The Pecten conglomerate (Pleistocene) on Cockburn Island is now more than 500 feet above sea level, indicating that some of the uplift of the peneplain in the northern part of the Palmer Peninsula has taken place since the conglomerate was deposited (Andersson, 1906, p. 50–53; Hennig, 1911).

Holtedahl (1935, p. 12, 27–28) recognized a dissected plateau in the northern part of the Palmer Peninsula. He interpreted it as an elevated erosion surface which he attributed to peneplanation.

Shore Line of Submergence

The Palmer Peninsula is an excellent example of a shore line of submergence and of a fjord coast. High bedrock islands, imposing promontories, irregular offshore profiles, and high-walled fjords indicate that a mountainous area was submerged. The submergence must be due in part, at least, to the weight of the ice. It is not known whether it is also due to a depression of this part of the continent unrelated to glaciation. The continental shelf around the Antarctic is the deepest in the world (Shepard, 1948, p. 141). Along the west coast of the Palmer Peninsula between 65°00′S. and 68°00′S. the break in slope appears to be between 1400 and 1600 feet (U. S. Navy Dept. Hydrog. Office, 1939) (Fig. 4). The average depth for the break in slope, based on a study of the continental shelves of the world, is 432 feet (Shepard, 1948, p. 143). A rough measure of the submergence of the Palmer Peninsula is, therefore, 1000 feet.

Cliffs thousands of feet high, common along the fjords and on the promontories, could have been formed by marine erosion, glacial erosion, or faulting. No evidence of large-scale faulting was observed during the reconnaissance field work. No wave-cut platforms associated with the cliffs and related to the present or earlier positions of sea level were seen (no submarine profiles or careful studies were made, however). The severity of the glaciation and the absence of faulting and wave-cut platforms indicate that the cliffs were formed, therefore, mainly by glacial erosion. The presence of the islands, promontories, and drowned valleys and the apparent absence of wave-cut platforms suggest that the area is in the initial or youthful stage of the marine cycle.

Following the uplift, the peneplain was considerably dissected. The area was depressed in the Pleistocene after the uplift and dissection of the peneplain and after the elevation of the Pecten conglomerate (Hennig, 1911).

Pre-Pleistocene Antarctic Glaciation

Because the Antarctic icecap has persisted long after the continental icecaps which covered North America, Europe, and other places have disappeared, it might seem logical to assume that glaciation was initiated in the Antarctic before it started elsewhere. If, however, the conditions which brought on glaciation appeared suddenly and were of wide distribution, the beginnings of glaciation may have been nearly synchronous on all the continents.

Wright and Priestley (1922, p. 183, 431–435), Priestley (1923, p. 10–11), and Gould (1939, p. 739; 1940, p. 868–869) believe that glaciation started in the Antarctic in the Tertiary.

Gould (1940, p. 869) writes,

> "According to Wright and Priestley (1922, p. 183) the intercalated layers of ice and volcanic debris on the slopes of Mount Erebus on Ross Island at the northwest apex of the Ross Shelf Ice indicate that glaciation must have begun there in early Tertiary,"

and elsewhere he writes (1939, p. 739),

> "The relationship of volcanic debris to intercalated layers of ice about Mount Erebus indicates that glaciation must have begun there in the Middle Tertiary (Wright and Priestley, 1922, p. 183)."

A reading of Wright and Priestley shows that Gould has misquoted them and that they do

not believe in Tertiary Antarctic glaciation because of the presence of ice interbedded in volcanic material on the slopes of Mount Erebus.

If volcanic material is actually interbedded with ice on Mount Erebus, and T. W. E. David (*in* Shackleton, 1909, p. 185, 194–195) who made the observations was not sure that this was the case, it still does not indicate a Tertiary age for the ice, as the volcanic material was seen on the walls of the active crater of Erebus. The active crater is undoubtedly post-Wisconsin, probably historic, and perhaps only a few hundred years old. The active crater is higher than 12,000 feet above sea level, and Debenham (1923, p. 37) feels that that part of the volcano above 11,000 feet may have changed greatly since Ross first viewed it in 1841.

Andersson (1906, p. 42) described a deposit at Cape Hamilton, James Ross Island, Palmer Peninsula as follows (*See also* Nordenskjöld, 1911, p. 107–108):

"Next above the Cretaceous beds follows a moraine-like mass, some meters in thickness: in a clayey matrix lie numerous angular fragments of crystalline rocks foreign to the locality (granite etc.; no volcanic rocks or porphyries were noticed amongst these fragments of plutonic eruptives and crystalline schists). Also pieces of claystone were noticed. The largest of these lumps of foreign rocks did not exceed half a meter in diameter; most of them were much smaller."

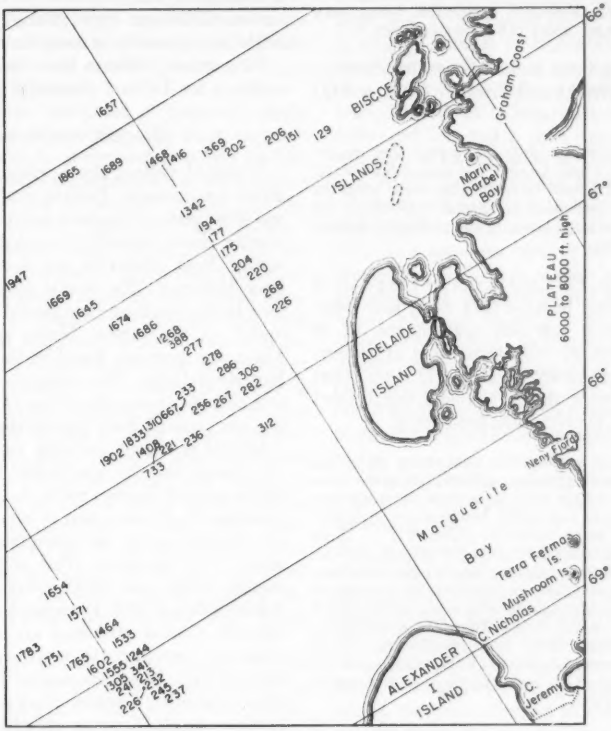

FIGURE 4 —U. S. NAVY DEPARTMENT, HYDROGRAPHIC OFFICE CHART NO. 5411
Depth in fathoms

In discussing this deposit Wright and Priestley (1922, p. 431–432) write,

"It appears probable... that in this moraine-like bed above the Cretaceous... we have visible evidence of one swing of the climatic pendulum as the Tertiary refrigeration set in. Angular rock fragments in a clayey matrix are strongly suggestive of glacial action on a comparatively large scale."

In a description of bedrock between Cape Karl Andreas and Cape Gunnar, Palmer Peninsula, Andersson wrote (1906, p. 29),

"Here a shore-nunatak exhibits a coarse conglomerate with boulders of up to 2 meters in diameter.

In general the mass is quite unstratified and really much like a bottom-moraine, though the rock is evidently old and seems to have taken part in the mountain-folding. Only in one spot, where the conglomerate is less coarse, does it show slight indications of bedding. The material of the pebbles is very varied, beautiful porphyries being very common amongst many other kinds of rock."

In evaluating these two localities described by Andersson, Wright and Priestley (1922, p. 432) write,

"... it is therefore quite likely that the two deposits may have been more or less contemporaneous. If this is so, it should be noted that these form the first definite evidences of glacial conditions, on anything like a large scale, in the geological history of the Antarctic, ..."

Cape Adare, East Antarctica, is composed of slightly dipping basaltic lava flows and intercalated beds of tuff and agglomerate, all of which are cut by numerous dikes (Priestley, 1923, p. 8). Priestley (1923, p. 11) found what he thought were glacial boulders interbedded in this series. He noted the presence of

"... a coarse agglomerate containing numerous foreign boulders—granites, schists, trachytes, porphyries, etc.—which both from their heterogeneity and the shape of individual boulders are undoubtedly glacier borne erratics (Plate 11).... Here we have undoubted evidence of the extension of the Ice Age back into the past, so far that glacial action, probably on a scale greater than that at the present day, was contemporaneous with some of the earlier of the Cape Adare lavas. Taken in conjunction with the evidence from West Antarctica... it is strong presumptive evidence of the existence of an advanced stage of a Glacial Cycle in Antarctica in mid-Tertiary times."

The Antarctic breccias described heretofore, which prove Tertiary Antarctic glaciation according to Wright and Priestley, are not, so far as is known, resting on glaciated basements, nor are they found with the deposits with which tillites are commonly associated. The only criteria presented which suggest a glacial origin for these breccias are clayey matrix, angular and triangular fragments, lack of stratification and sorting, and fragments composed of a variety of lithologic types (Sayles, 1914, p. 144–145; Wentworth, 1936, p. 91–92). These features, however, are also characteristic of mudflows, volcanic breccias, and fanglomerates. The breccias in question are associated, at two of the three localities considered by Wright and Priestley, with tuff and agglomerate, suggesting that they are also of volcanic origin.

Nordenskjöld (1911, p. 107–108), in his discussion of the morainelike deposit at Cape Hamilton, James Ross Island, Palmer Peninsula, pointed out that some of the fragments came from distances as great as 50–60 km and were therefore probably ice-laid. The deposit is associated with volcanic breccias, and the various lithologic types foreign to the area might just as well have come from depth.

This writer, believes that there is no good evidence for Tertiary Antarctic glaciation.

Glacial Features

U-shaped valleys, fjords, cirques, horns, and arêtes are common. Erratics and a discontinuous thin veneer of moraine are found above the marine limit. Smooth, rounded surfaces resulting from glaciation are found at Roman Four Mountain (Fig. 3) and other places. Bedrock basins resulting from glacial plucking were found on Stonington Island and elsewhere. Truncated spurs are found on the north side of Red Rock Ridge. They suggest that hundreds and perhaps thousands of feet of valley widening has resulted from glacial erosion.

Glacial striations are very rare. They were not found on the mainland. However, the coarse-grained igneous rocks on two islands approximately 50 miles west of Stonington Island are striated, and at one place they have glacial grooves and trenches. The argillites on two islands which are 10–15 miles southwest of Adelaide Island (Fig. 4) are in places excellently striated. Glacial striations are scarce on the mainland because: (1) wave action has destroyed those below the marine limit; (2) frost action and other processes have destroyed them in other places; (3) coarse-grained igneous rocks which are the most common rocks on the mainland are not easy to striate, nor are striations preserved on them as long as on some other rock types; and (4) the basal load moved by the glaciers was not great.

Deglaciation

The deglaciation of the Palmer Peninsula has been described by Arctowski (1900b, p. 479–481; 1908, p. 59–64), Nordenskjöld (1904, p. 360; 1911, p. 168–174), Andersson (1906, p. 53–57), Nordenskjöld and Andersson (1905, p. 225, 466), Gourdon (1908, p. 116–121), Holtedahl (1935, p. 118–119), Fleming *et al.* (1938, p. 510), Stephenson and Fleming (1940, p. 160), Fuchs (1951, p. 413), and Nichols (1953, p. 20–39).

A small cliff glacier on the north side of Red Rock Ridge (Fig. 3) near its western end reaches

tidewater. A steep slope veneered in part with talus is located on the north side of the ridge immediately east of the cliff glacier. A flat approximately 1500 feet above sea level is located near the top of the ridge immediately above the slope. The country rock on the slope, on the flat, and on all parts of the ridge immediately to the east is a red granite (Nichols, 1955, p. 24–28, Fig. 39).

A felsenmeer composed of fragments easily differentiated from talus (the fragments are slightly rounded and weathered) covers the flat. Fragments of the red granite are very abundant; others composed of whitish granite, diorite, gabbro, pyrobolite, pyroclastic and plutonic breccias, banded felsite, gneiss, and schist are present. Some fragments are pitted and differentially weathered. One fragment showed striations. The red granite intrudes all these rock types. These fragments cannot have been inclusions in the red granite which were weathered out in postglacial time because the granite is singularly free of inclusions, no red granite was seen adhering to any of these fragments, and because of the slight rounding and weathering of fragments. The rocks which these fragments are composed of are all found *in situ* at the eastern end of the fjord (Nichols, 1955, Table 1). Small patches of till are also found on the flat. The fragments and the till were deposited on the flat by the Neny Glacier when it extended many miles west of Red Rock Ridge (Fig. 3).

On the ridge east of the flat, erratics and till were found with increasing spareness up to 1700 feet. The glacial limit is probably higher, as the ridge is steep, and material tends to move down-slope. A figure of 2000 feet for the former thickness of the ice at this point seems conservative if the depth of the water in the fjord is considered and if something is added for the thickness of the ice above the position at which the highest erratic was found. The flat is approximately 12 miles west of the present terminus of the Neny Glacier. The gradient of the Neny Glacier when it covered this area is not known, but 100 feet per mile seems conservative. This suggests that the ice must have been approximately 3000 feet thick at the present terminus of the Neny Glacier at one time. Red Rock Ridge and Neny Island (Fig. 3) must have been nearly or completely covered with ice; Stonington Island was probably under 2000 feet or more of ice, and the whole Palmer Peninsula was probably covered with a more or less continuous icecap which extended many miles westward into Marguerite Bay.

The Terra Firma Islands, consisting of one large island and at least nine much smaller ones, are located in Marguerite Bay at approximately 68°45′S. and 67°31′W. and are about 15 miles west of the barrier (ice cliff) on the mainland (Fig. 3). The coast line of the main island is roughly 2 miles in circumference; a barrier occurs along most of it, and on the northwest side of the island bedrock comes down to sea level. The island in large part is covered with snow and ice, and a peak approximately 500 feet high is its dominant feature.

A relatively flat area of several acres, from which the main peak of the island has a bearing of N.350°E., occurs at an elevation of about 300 feet. This area was bare in the latter part of November 1947. It is mainly a felsenmeer of fragments of many different sizes and rock types, although bedrock crops out in a few places. The country rock is a dark-gray pyroclastic felsitic breccia cut by a few trap dikes (Nichols, 1955, p. 10–12). The breccia is composed mainly of felsitic fragments but also has fragments of granite, aplite, gabbro, and granite gneiss.

Most of the fragments in the felsenmeer are gray pyroclastic breccia. There are, however, thousands of fragments of pink granite; diorite, gneiss, trap, felsite porphyry, and other rock types are also present. Some fragments are as much as 12 feet long. One fragment of trap showed glacial striations. The pink-granite fragments were not weathered out from the felsitic pyroclastic breccia as they are much too large and numerous and have no felsitic material adhering to them. They were not deposited by sea ice or icebergs, as the marine limit for this area is much lower (Nichols, 1947a), and no evidence of marine action was seen on the flat. They are glacial erratics. Similar pink granite is found on the mainland, and it is probably present below sea level between the mainland and the islands (Nichols, 1955, p. 12–13). These erratics prove that the mainland ice once extended out to and beyond the Terra Firma Islands. Fragments of pink granite and of other rock types were plucked from outcrops on the mainland and from ledges between the mainland and the islands and were deposited on the flat. The writer did not climb the 500-foot peak on the island and so did not determine precisely the upper limit of glaciation. The ice must have had considerable thickness above the flat, however, in order to be able to drop on it erratics 12 feet long. It must have been at least 500 feet thick in this area; it undoubtedly

extended 5 or more miles beyond the islands, and it was probably at one time 2000 or more feet thick at the site of the present barrier on the mainland (Fig. 5).

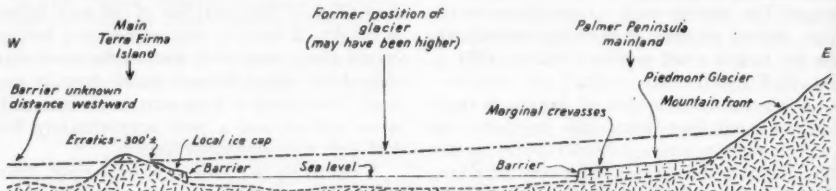

FIGURE 5.—FORMER EXTENSION OF THE ICE AT TERRA FIRMA ISLANDS, ANTARCTICA

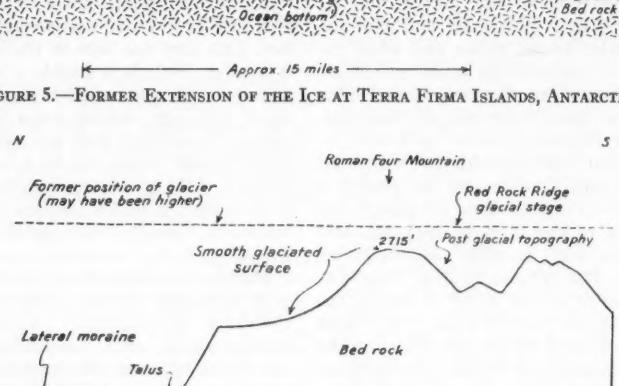

FIGURE 6.—UPPER LIMIT OF GLACIATION AT ROMAN FOUR MOUNTAIN, ANTARCTICA

Roman Four Mountain (Fig. 3), about 2700 feet high, projects about 1½ miles southwestward into Neny Fjord. A valley glacier with a prominent lateral moraine on its southern edge lies immediately to the northeast. Above the glacier, approximately 1300 feet above sea level, there is a smooth, flattish bedrock surface which contrasts sharply with the steep rough-surfaced cliffs below it. This smooth surface continues upward with increasing steepness. The summit is a small, smooth, round dome. To the southwest is a ridge of lower, saw-toothed peaks. These features (Fig. 6) can be seen clearly from Stonington Island. The writer believes that the smooth, flattish surface and the roundish summit are due to glacial erosion. The surface of the ice in this area at the time the smooth surfaces were formed must have been 3000 or more feet above the present sea level. Following deglaciation, parts of the smooth glaciated surfaces were destroyed by the headward growth of the cliffs, and talus accumulated at the foot of the mountain.

The smoothed surfaces, bedrock basins, and the location of the Northeast Glacier, as well as data from Red Rock Ridge, Roman Four Mountain, and elsewhere, prove that Stonington Island was glaciated. Elevated beach gravel is found 70 feet above sea level on Stonington Island (Nichols, 1947a). Since deglaciation, the land has gone up with respect to the sea perhaps 60 or more feet; yet, in 1948 the barrier of the Northeast Glacier was in places less than one-quarter of a mile away from the island. No data were obtained on the rate of uplift. If, however, a rate of 10 feet per century is assumed—and this is twice as rapid as the present rate of uplift in the Canadian Northwest Territories (Washburn, 1947, p. 73)—then it appears that the Northeast Glacier has retreated less than one-quarter of a mile in 600 years. Elevated beaches 50 feet above sea level are found on Neny Glacier Island (unofficial name) only a few hundred

yards from Neny Glacier (Fig. 3). It is not known whether the present terminal positions of the Northeast and Neny glaciers are due to a very slow glacial retreat or to a more rapid retreat followed by a readvance.

Data on the remarkable rate of retreat of the shelf ice in King George VI Sound (Fig. 3) from 1940 to 1949 are furnished by the observations of Ronne and Fuchs. When Ronne and Eklund visited Eklund Island, a rocky nunatak more than 1000 feet high in the southwestern part of King George VI Sound, in December 1940, it was surrounded by shelf ice, and the edge of the shelf ice was approximately 30 miles to the northwest (Ronne, 1945, Map 1; 1948, Fig. 1). Fuchs and R. J. Adie found bay ice at the foot of the island in November 1949 (Fuchs, 1951, p. 411; Fig. 4). The edge of the shelf ice had, therefore, retreated approximately 30 miles in this area in this 9-year interval.

The edge of the shelf ice at the northern end of King George VI Sound is likewise rapidly retreating. The eastern side of the barrier was approximately 12 miles south of Cape Jeremy when mapped by Stephenson (1940, p. 232) in 1937. Members of the Falkland Islands Dependencies Survey found in 1948 that the western end had retreated between 25 and 30 miles in this 11-year interval and that the eastern end had retreated about 15 miles (Fuchs, 1951, p. 405; Fig. 2). Ronne (1948, p. 362) also had noted this retreat. He wrote, "Our plane flights . . . revealed . . . that the face of the shelf had moved back 35 miles in seven years."

If these rates of retreat continue, the bulk of the shelf ice in King George VI Sound will have disappeared in a few hundred years.

A comparison of Figure 1 of Plate 1, a photograph of Stonington Island and the Northeast Glacier taken by the U. S. Antarctic Service Expedition in November 1940, with Figure 2 of Plate 1, a photograph of the same area taken by the Ronne Antarctic Research Expedition in April 1947, indicates that the Northeast Glacier has retreated measurably in this 6½-year interval. Captain Finn Ronne (Personal communication) believes that the Northeast Glacier in places near Stonington Island has retreated more than 200 feet in this interval. A comparison of photographs taken of the Neny Glacier in 1940 and 1948 (Pl. 1, fig. 3; Pl. 2, fig. 1) suggests that the south side of Neny Glacier has retreated hundreds of feet in this interval. The four photographs given herein should prove valuable to future students of the deglaciation of this area.

Strand Flats

A well-developed strand flat is located along the south side of Neny Fjord at the foot of Neny Fjord Thumb (unofficial name) (Fig. 3). It is bounded on the north and east by water and on the south by talus slopes and bedrock cliffs; to the west it narrows and terminates against bedrock slopes. It is about 1500 feet long, more than 400 feet wide for most of its length (Fig. 7), and is in places as much as 20 feet above sea level. It is highest at the southeast, from which it slopes gradually approximately to sea level to the northwest. Till and elevated beach gravels in places veneer this strand flat, and felsitic boulders dot its surface (Figs. 7, 8; Pl. 3, fig. 1). The till rests on a bedrock platform, and beach gravels as much as 4 feet thick and as much as 20 feet above sea level in places bury the till (Fig. 8).

The truncated spurs of Neny Fjord indicate that in places it has been widened hundreds of feet by glacial erosion. It seems likely, therefore, that the bedrock platform is not a preglacial marine terrace. The fact that till veneers the bedrock platform and that the platform slopes along its seaward margin from about 20 feet above sea level at the southeast to a point below sea level at the northwest proves that it is the result of glacial erosion and not of postglacial marine erosion. It was probably formed by the glacier which is now immediately southeast of the strand flat.

The felsitic boulders vary greatly in size. One about 20 feet high and 30 feet long was measured. The largest are at the southeast end of the strand flat; the boulders decrease in size toward the northwest. Small ponds are found in the depressions between the boulders. Talus aprons surround them. A few debris cones were seen, and here the original boulders are completely buried in their own debris (Taylor, 1922, p. 69–73). The weathering and erosion of the boulders has also resulted in the formation of mushroom rocks, pinnacles, and oddly shaped boulders (Pl. 3, fig. 1). The writer believes that the boulders were transported and deposited by the glacier which cut the strand flat and deposited the till. The largest boulders are at the southeast end of the strand flat, and the boulders decrease in size toward the northwest, supporting the idea that the glacier which cut the strand flat and deposited the till came from the southeast.

Following the erosion of bedrock by the glacier, the deposition of the till and the boulders, and the deglaciation of the area, the

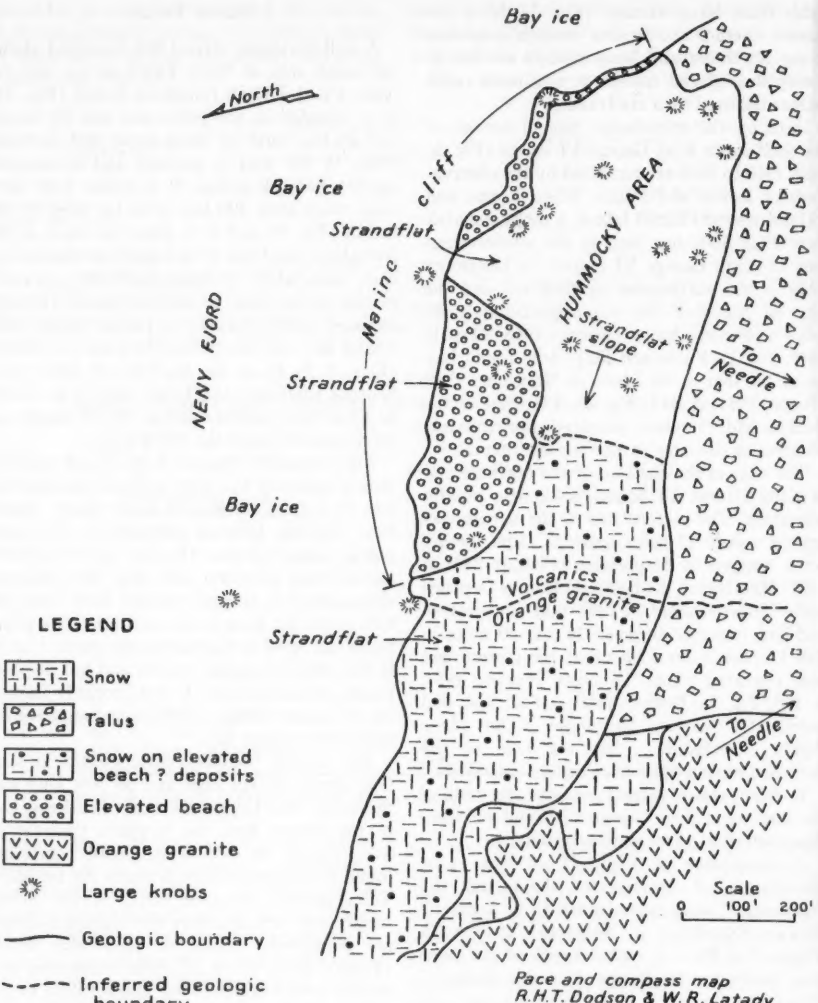

FIGURE 7.—GEOLOGIC MAP OF THE STRAND FLAT NEAR NENY FJORD THUMB (UNOFFICIAL NAME), ANTARCTICA

strand flat was invaded by the waters of the fjord, and the beaches were formed. Following the formation of the highest beaches, sea level dropped as much as 20 feet in relation to the land. Talus is forming at present and is progressively burying the strand flat.

A prominent strand flat on the north side of Neny Island is several hundred yards long, as much as 150 yards wide, and slopes gently seaward. It is cliffed on its seaward side and on its landward side is in most places talus-covered. The surface is covered with elevated beach gravels which, along the seaside cliff, rest on bedrock. The beach gravels are in places deeply buried by talus. The variation in the height of the bedrock surface on which the beach gravels rest indicates that it was cut by glacial rather than by marine action. The

fact that no prominent strand flat is found on the west end of Neny Island, where the waves are strongest and where the other factors such as topography and resistance of bedrock are presumably similar, supports this view.

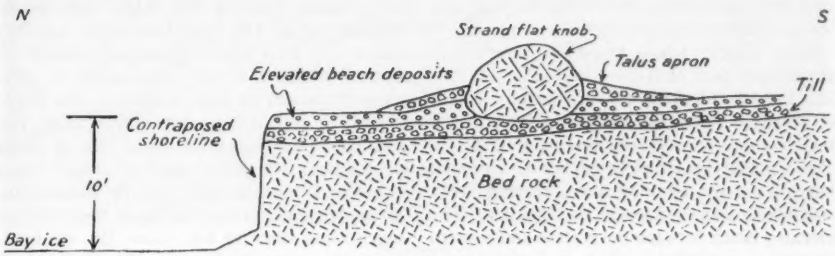

FIGURE 8.—CROSS SECTION OF STRAND FLAT

WEATHERING

Weathering produces well-developed vertical leaflike plates in gabbro and in places in pink granite in the bedrock on Neny Glacier Island (unofficial name) (Fig. 3). Most of the individual plates are between one-eighth and half an inch thick, less than 10 inches long measured in the horizontal, and a few inches measured in the vertical (Pl. 4, fig. 1). They may all be oriented in essentially the same direction over an area of several hundred square feet. Elsewhere adjacent plates may be at right angles. Areas of a few thousand square feet are completely covered by these plates. The plates are not significantly stained, and the gravel resulting from weathering appears fresh. It seems logical to suppose that these plates are the result of fracture cleavage or some other closely spaced foliation which has been opened up and widened by weathering. The absence of staining suggests that they are probably due in part, at least, to frost action. Gabbro absorbs more insolation than the lighter-colored rocks, and therefore freezing and thawing should be more prevalent in gabbro. This may explain why the feature is almost wholly confined to gabbro.

Bedrock, angular fragments, and roundstones on the upper and older parts of the elevated beaches on Stonington Island (Fig. 3) are commonly pitted at the surface. The pits range in width from a fraction of an inch up to 3 inches or so, and they may be more than 1 inch deep. A square foot of rock surface may have as many as 100 pits (Pl. 4, fig. 2). They give the rocks a vesicular appearance. The pitted rock is not hard, as the surface can be broken off by pressure with the fingers or hand. The rocks are not stained by limonite or other minerals. The pits are common on the mafic rocks, very uncommon on the felsic rocks. These pits are not the result of corrasion by wind-blown snow, dust, or sand because: (1) the smooth, polished, fluted, facetted surfaces with the cuspate hollows and interfacet edges which characterize ventifacts (Mather, Goldthwait, and Theismeyer, 1942, p. 1167–1170) are not found on these pitted rocks or on the other rocks in the area; (2) the pitted surfaces would be hard, not crumbly, if eolian action were important in their formation; (3) significant quantities of wind-blown dust or sand were not seen either in the air, on the ground, or on the snow; (4) the temperatures (Peterson, 1948a, p. 7) are not low enough to give ice the hardness necessary for wind-blown snow to corrade igneous rocks (Teichert, 1939; Blackwelder, 1940); (5) the snow is so plentiful that the rocks are continuously and completely covered during the cold season; (6) the pits are probably too deep and narrow to have been produced by eolian action. Some of the flakes and grains, however, which are loosened from the rocks by weathering processes are probably removed by the wind. The lack of staining suggests that mechanical weathering may be important.

The mafic rocks in this area weather more rapidly than the felsic. This is shown by the gabbro inclusions which are commonly weathered below the surface of the granitic country rock and by the scarcity of pits and leaflike plates in the felsic rocks. The relative importance of chemical and mechanical weathering cannot be evaluated, however, on a basis of these field observations.

Elevated Beaches

More than 20 well-developed elevated beaches are found in the Marguerite Bay area (Table 1). This is perhaps surprising, as at some of these localities the sea is open for only two, three, or four months during the year, and in most places a barrier coast line is present.

Neny Glacier Island (unofficial name) is in the eastern part of Neny Fjord (Fig. 3). It is less than a mile long, and the eastern end is attached to Neny Glacier. The island in the main consists of an eastern and western section tied together by an elevated beach. Elevated beaches are also found on the northwest, west, southwest, and south sides of the island. The elevated beach between the eastern and western sections is a tombolo and at its highest point is approximately 50 feet above sea level. Not only were the western and eastern sections separated during the high stand of the sea, but the eastern section itself was also separated into four or more individual islands. A well-developed, extensive, elevated ridged boulder beach on the southwest part of the island extends up to approximately 50 feet above sea level.

Raised beaches are very common on the east and north sides of Neny Island (Fig. 3). Those on the east side extend up to nearly 50 feet above sea level, cover extensive areas, and have well-developed beach ridges. On the north side of the island, elevated beach gravels are as much as 90 feet above sea level. In places they were deposited on a strand flat and are being progressively buried by talus and alluvial-fan deposits; rock fragments formed by the shattering of talus blocks and beach roundstones are found on them. Shallow pits several feet in diameter on the beach ridges were probably formed by stranded growlers which melted away after being either buried or surrounded by beach gravel.

There are many elevated beaches near the western end of Red Rock Ridge (Fig. 3). The highest is on the north side at the entrance to a north-south chasm which cuts across the westernmost part of the ridge. This beach extends up to 110 feet (barometric reading) above sea level and is composed mainly of large boulders 1–3 feet in diameter. A talus slope composed of huge fragments lies above the beach and perhaps buries some of it. The angular talus fragments stand out in sharp contrast to the round and subround beach boulders. It seems unlikely that the roundstones in the highest part of the beach were formed much more than 10 feet above the sea level. Approximately 100 feet of uplift of the land relative to the sea is therefore indicated for this area. The most prominent and extensive beach is on the south side of Red Rock Ridge. It extends westward from the barrier, past a block terrace, almost to the penguin rookery. It is approximately 2000 feet long and in places somewhat more than 30 feet above sea level.

An excellent example of an elevated pocket boulder beach is located on an unnamed island between the Refuge Islands and Black Thumb Mountain (Fig. 3). It is more than 200 feet long and 600 feet wide; it extends 27 feet above sea level and has beach ridges on it. Beach roundstones were found as much as 19 feet above it (Pl. 3, fig. 2). Pitted rock and heaps of granules due to weathering are found on the upper part of the beach. Other less extensive and lower elevated beaches are also present on this island.

An elevated beach on the mainland at Black Thumb Mountain (Fig. 3) covers many acres. The upper part of it is approximately 25 feet above sea level and several hundred feet from

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Plate 1.—AERIAL PHOTOGRAPHS OF THE NORTHEAST AND NENY GLACIERS, ANTARCTICA

Figure 1.—Aerial photograph showing the relationship of the barrier of the Northeast Glacier to Stonington Island in November 1940.

Figure 2.—Aerial photograph taken in April 1947, showing the relationship of the barrier of the Northeast Glacier to Stonington Island.

Figure 3.—Aerial photograph showing the position of the terminus of Neny Glacier in November 1940.

Plate 2.—ANTARCTIC GLACIERS

Figure 1.—The south side of terminus of Neny Glacier in 1948, showing crevasses and formation of icebergs. Bay ice folded and cracked by thrust of glacier. Cirques, horns, arêtes, and the highland ice flowing off the plateau in an outlet glacier are visible.

Figure 2.—Highland icecap and outlet glacier east of Stonington Island.

Figure 3.—Piedmont glacier and barrier, Alexander I Island.

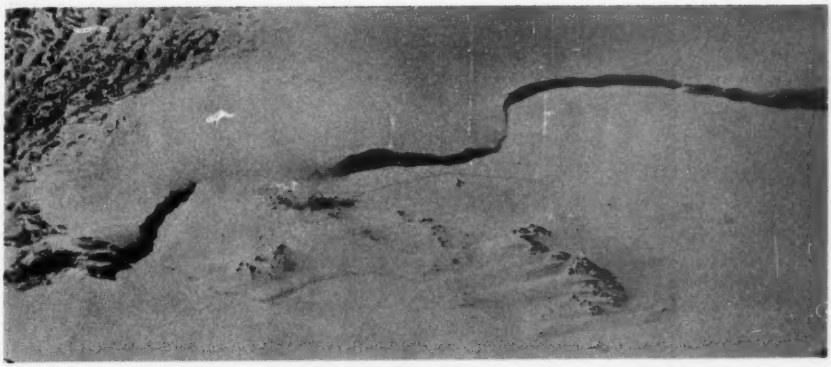

FIGURE 1

FIGURE 2

FIGURE 3

AERIAL PHOTOGRAPHS OF THE NORTHEAST AND NENY GLACIERS, ANTARCTICA

FIGURE 1

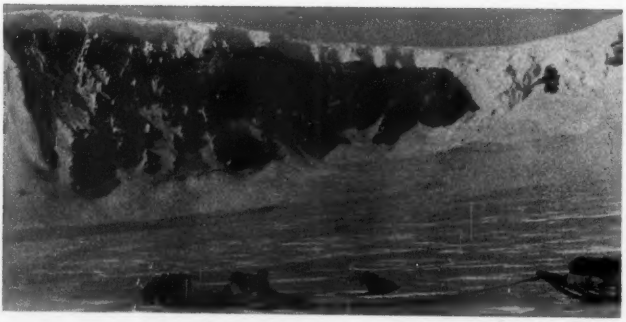

FIGURE 2

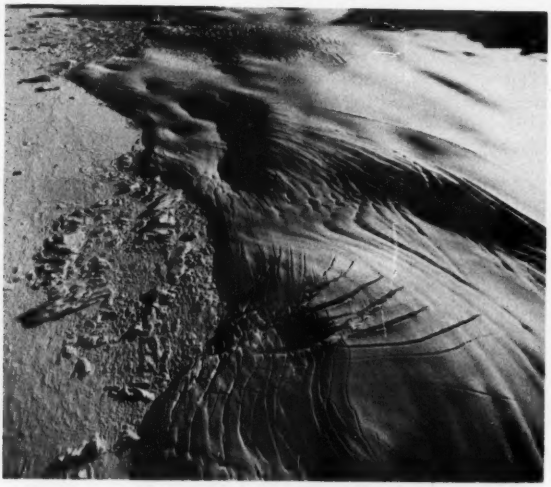

FIGURE 3

ANTARCTIC GLACIERS

FIGURE 1

FIGURE 2

FIGURE 3

STRAND-FLAT AND ELEVATED BEACHES, ANTARCTICA

FIGURE 1

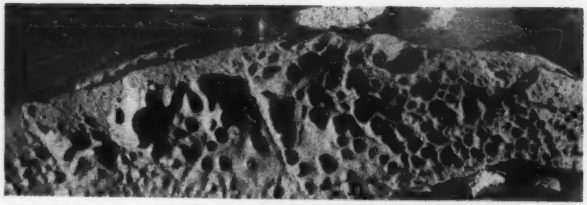

FIGURE 2

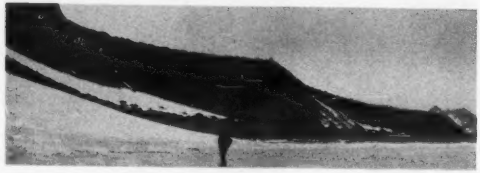

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

EXAMPLES OF WEATHERING, BLOCK TERRACES, BRASH AND GROWLER ICE FIELD, SNOWDRIFT ICE SLABS, AND SYNCLINAL PONDS, ANTARCTICA

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the present strand line, and it is being progressively buried by talus.

A large part of Stonington Island (Fig. 3) is covered with well-developed elevated cobble and boulder beaches. The highest part of the island is approximately 80 feet above sea level, and beach gravels extend up to 70 feet. Only small, bare, bedrock knobs project above the beach gravels (Pl. 3, fig. 3). During the highest stand of the sea the island was probably submerged; later, several small bedrock islands were present; still later, pocket beaches, tied islands, and tombolos were formed. Continued emergence finally resulted in the present configuration of the island. Beach ridges occur but are not prominent. The upper, older parts of the beaches which are close to the bedrock knobs are veneered with chips and flakes spalled from the knobs. On the older parts of these beaches, many of the roundstones of mafic composition are pitted. The pits are numerous, well-developed, and commonly more than an inch deep. The felsic coarse-grained roundstones on the older parts of the beaches are commonly roughened by exfoliation, and accumulations of spalled fragments commonly surround them (Nichols, 1947a). Roundstones split and shattered by frost action are also not uncommon on the older parts of these elevated beaches.

These elevated beaches were identified primarily by the abundant roundstones above sea level, topography which slopes down to sea level, and beach ridges roughly parallel to the high-tide mark. No organic remains were seen in these beach deposits, probably because these beaches are composed mainly of cobbles and boulders so that organic material on the beach face is quickly destroyed by crushing and attrition.

Deciding whether a beach has been elevated is often difficult because it is not easy to determine how far above sea level gravel can be thrown by wave action on any particular beach. The roundstones on some of the beaches contain dark minerals. On these beaches the roundstones above the zone of wave action showed limonite staining. The limonite line above which the roundstones were stained and below which they were not stained was used to separate the active part of the beach from the elevated inactive part. Its existence demonstrated the presence of an elevated beach. It enabled estimation of the amount of the uplift of the land relative to the sea which was necessary to account for the altitude of the raised beaches.

The major topographic features of these beaches are due to the slope of the bedrock and ground moraine on which the beach gravels rest. Ground moraine is the most important source for the material of these beaches. Talus is a much less important source. The insignificant amount of postglacial marine crystalline bedrock erosion indicates that here as elsewhere this does not produce a significant supply of beach material. The elevated beaches, in places, slope down from the marine limit to the ocean in a smooth, continuous, gently inclined plain, indicating that no significant stillstand of sea level has taken place during their development. These elevated beaches are being buried in places by talus, alluvium, and fringing glaciers and snowdrift ice slabs.

The elevated beaches in Graham Land have been described by Andersson (1906, p. 57–59),

PLATE 3.—STRAND-FLAT AND ELEVATED BEACHES, ANTARCTICA

FIGURE 1.—Elevated beach gravels, boulders, and mushroom rocks on the strand flat, Neny Fjord Thumb (unofficial name).

FIGURE 2.—Elevated beach 27 feet above sea level on an island between Black Thumb Mountain and Refuge Islands. Bay ice and barrier in the background.

FIGURE 3.—Elevated beach ridge scores of feet above sea level. Many roundstones, pitted and roughened by weathering. Stonington Island.

PLATE 4.—EXAMPLES OF WEATHERING, BLOCK TERRACES, BRASH AND GROWLER ICE FIELD, SNOWDRIFT ICE SLABS, AND SYNCLINAL PONDS, ANTARCTICA

FIGURE 1.—Vertical plates in gabbro formed by weathering, Neny Glacier Island (unofficial name).

FIGURE 2.—A fretted surface resulting from the weathering of a mafic fragment found on Stonington Island.

FIGURE 3.—Two block terraces on southwest side of Roman Four Mountain.

FIGURE 4.—Brash and growler ice field next to Northeast Glacier.

FIGURE 5.—The snowdrift ice slabs on Stonington Island in foreground.

FIGURE 6.—Synclinal fresh-water ponds on bay ice folded by the thrust of Neny Glacier.

TABLE 1.—ELEVATED BEACHES OF MARGUERITE BAY, PALMER PENINSULA, ANTARCTICA

Location	Maximum Altitude	Area Dimensions	Special Features	Remarks
Mushroom Island	Approximately 20 feet	Small	..	Being buried by talus
Moraine Point (unofficial name)	Approximately 20 feet	Small	..	Beach roundstones intermingled with moraínal fragments
Black Thumb Mountain	25 feet	Many acres	..	Upper part several hundred feet from strand line. Upper part being buried by talus
Small unnamed island between Black Thumb Mountain and Red Rock Ridge. Bearing to center Bingham Col N. 25°E. Bearing to Black Thumb Mt. N. 127°E.	12 feet	..	..	Elevated?
Small unnamed island near Black Thumb Mountain	Above sea level	Small; in a chasm	..	Elevated?
Small unnamed island between Black Thumb Mountain and Red Rock Ridge	27 feet	200 feet long, 600 feet wide	Pocket beach	Beach ridges. Beach roundstones up to 46 feet. Other slightly elevated beaches
Red Rock Ridge (north side)	110 feet		Coarse boulder beach	Highest beach in the Marguerite Bay area
Red Rock Ridge (south side)	Somewhat more than 30 feet	2000 feet long	..	..
Neny Island (east side)	Nearly 50 feet	Extensive	Well-developed beach ridges	..
Neny Island (north side)	90 feet	Extensive	On strand flat in places	Buried by talus and alluvial-fan deposits in places; pitted beach ridges
Roman Four Mountain	Slight elevated	..	..	At least three small beaches
Bingham Col (east corner)	Approximately 30 feet	..	..	..
Neny Fjord Thumb (unofficial name)	More than 20 feet	Extensive	On strand flat	..
Neny Glacier Island (unofficial name)	Approximately 50 feet	Extensive	At northwest side, beach cliffed at strand line	In part elevated tombolos. Many areas
Islands 50 miles west of Stonington Island	Above sea level	..	..	Two small beaches—elevated?
Two islands 10–15 miles southwest of Adelaide Island	Above sea level	..	..	Two small beaches—elevated?
Stonington Island	70 feet	Cover large part of island	Crescentic scars. Pitted roundstones	..

TABLE 2.—ANTARCTIC ELEVATED BEACHES, MARINE CAVES, MARINE TERRACES

Location	Altitude	Remarks	Observer or Authority
Cockburn Island, Graham Land	13 feet	Beds of sand and gravel	Andersson (1906, p. 57–58)
Hope Bay, Graham Land	10 feet above sea level, perhaps higher	Numerous rounded pebbles not now reached by waves	Andersson (1906, p. 57)
Sidney Herbert Sound, Graham Land	About 13 feet	Marine stratified bouldery fossiliferous clay. Marine till. Deposited below sea level	Andersson (1906, p. 58–59)
West Antarctica	32–49 feet	..	Nordenskjöld (1913, p. 14)
Jenny Island, Marguerite Bay, Graham Land	26 feet	Elevated beach, 1300–1600 feet long; 160–330 feet wide. Whalebone	Bongrain (1914, p. 49)
South of Adelaide Island, Graham Land	80 feet	Many beaches	Fleming (1940, p. 94, 97)
Cape Barne, Ross Island, South Victoria Land	180 feet	Sponge spicules, serpulae, molluscan shells. Probably not a beach	David and Priestley (1909, p. 317–318)
Cape Bernacchi, South Victoria Land	100 feet	Terraces suggestive of raised beaches	David and Priestley (1909, p. 318)
Terrace Island (20 miles north of Cape Bernacchi), South Victoria Land	80–85 feet	Terraces; sand and coarse gravel	David and Priestley (1909, p. 318)
Backdoor Bay, McMurdo Sound, Ross Island, South Victoria Land	160 feet	Diatoms, serpulae tubes, roundstones. Small area. Probably not a beach	Priestley and David (1912, p. 808–809)
Cape Geology, Granite Harbor, South Victoria Land	About 50 feet	One elevated beach	Taylor (1922, p. 22, 23)
Four miles east of Cape Geology, Granite Harbor, South Victoria Land	About 50 feet (top of cave)	Marine cave	Taylor (1922, p. 35–36)
Inexpressible Island, Evans Coves, Terra Nova Bay, South Victoria Land	About 80 feet	Raised boulder beach. Elevated seaweed	Priestley (1923, p. 53–56)
Taylor Valley (Dry Valley), New Harbor, McMurdo Sound, South Victoria Land	At least 50 feet	Numerous shells. *Pecten Colbecki, Anatina elliptica, Limatula.* Shallow-water deposit	Priestley (1923, p. 56–57)

Nordenskjöld (1913, p. 14), Bongrain (1914, p. 49), and Fleming (1940, p. 94, 97). The elevated beaches in South Victoria Land have been described by Taylor (1922, p. 22–23, 35–36) and Priestley (1923, p. 53–57). The highest beaches in both places are approximately 80 feet above sea level.

There is, therefore, good evidence that the margin of a large sector of the Antarctic Continent has been uplifted recently. It is generally agreed that this uplift is due to deglaciation (Priestley, 1923, p. 57; Washburn, 1947, p. 55–56; Daly, 1934, p. 112, 148). If, as indicated by Tables 1 and 2, the margin of the continent has been recently elevated 100 feet; if the elastic uplift is taken as one-fifth of the plastic uplift; if eustatic changes in sea level and the gravitational distortion of sea level due to glaciation are not considered; and if, further, the specific gravity of ice is taken as 0.92 and that of the plastic subcrustal material whose movement in toward the deglaciated area caused the uplift is taken as 3.5 (Personal communication, Francis Birch); then calculation shows that on the average the removal of approximately 300 feet of ice

was responsible for this uplift. This is undoubtedly a minimum figure for the thickness of the ice which has been removed during deglaciation because: (1) In Fennoscandia and the other regions where deglaciation has taken place, equilibrium of the crust was not achieved until long after the ice had disappeared (Daly, 1934, p. 65–69). It is unlikely that equilibrium has been reached, as raised beaches are found not far from the ice and deglaciation is still in progress. (2) More deglaciation probably took place before the beaches were formed than since. This is particularly true of the raised beaches on Neny Glacier Island (unofficial name) and on Stonington Island, as the ice has retreated only a short distance from these areas, and yet it was thousands of feet thick here and its terminal position was many miles to the west when it was full-bodied. These beaches can only record, therefore, a fraction of the crustal recoil resulting from deglaciation. (3) Still higher elevated beaches may be found as field work continues. A study of the raised beaches of the Antarctic strongly suggests that on the average a thickness of perhaps 1000 feet of glacial ice has been removed from the margin of the continent during deglaciation.

Talus

Huge talus slopes are found on Neny Island, at the foot of Roman Four Mountain, at Black Thumb Mountain, at Neny Fjord Thumb (unofficial name), and elsewhere. The abundance of talus indicates that the periglacial conditions found at these places favor its formation.

Talus cones and aprons hundreds of feet high are present on the east and north sides of Neny Island. Shallow scars or depressions are found on the leeward side of some of the cones where the snow accumulates in greater quantity and where it forms a more permanent ground cover. It is not known whether nivation is a factor in their formation. Evidence indicates that the scars may be due to a deficiency of deposition on the cones at these places because of the formation of pro-talus ramparts by the sliding downward of talus fragments on the snow slopes. Talus containing large blocks as well as fine material is found on the east side of Neny Island. Small patches of alluvium have been deposited on this talus in the depressions on the upslope side of some of these blocks. In this way alluvial flats were formed which have a surface area of a few square yards (Fig. 9). Water from melting snow and ground ice probably transported the alluvium. The presence of ground ice is probably necessary for the formation of the alluvium, as otherwise the water would sink into the talus and runoff

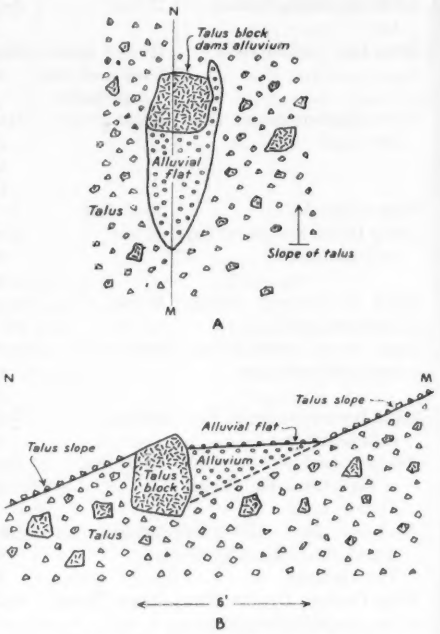

Figure 9.—Alluvium Deposited on Talus Slope

would not take place. Channels, levees, and irregular depositional topography on one of the talus cones on Neny Island cover several acres. The presence of ground ice in the talus no doubt facilitated their development.

Block Terraces

Block terraces which are below the snow line are found close to sea level on the north side of Neny Island, on the southwest and northwest sides of Roman Four Mountain (Pl. 4, fig. 3), and on the north, west, and south sides of Red Rock Ridge (Fig. 3). The terrace flat of one of those on the north side of Neny Island is approximately 300 feet long and 150 feet wide (Fig. 10). The flat has a 6-degree slope; it is covered with large angular blocks, randomly placed. The margins are slightly higher than the central portion, and a small talus cone has been built on it. The lower

terrace slope has a 37-degree gradient. The knickpoint formed at the boundary of the terrace flat and the lower terrace slope is sharp. A talus slope with a 30-degree inclination is found in a deep ravine immediately above the terrace flat. No data were obtained on the thickness of the layer of blocks on any of the terraces.

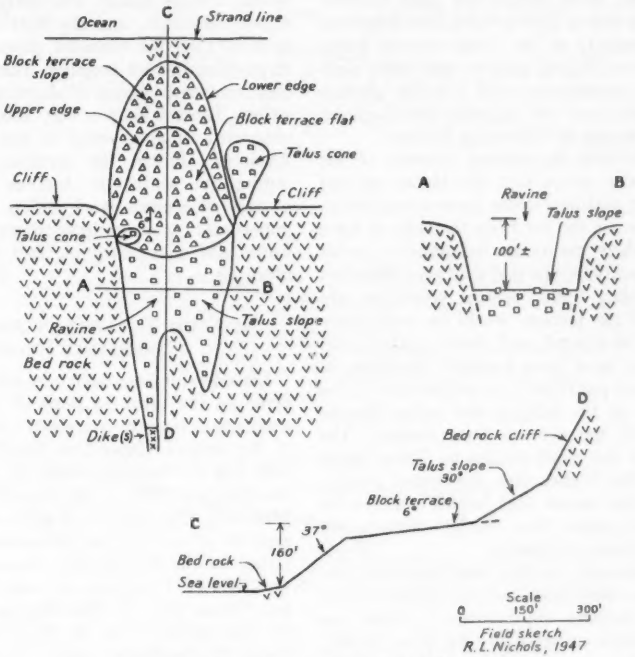

FIGURE 10.—FIELD SKETCHES OF BLOCK TERRACE

No water was seen or heard running between or beneath blocks; no melt water issued from the terraces, and no interstitial ice was seen. Nevertheless, the writer feels that an internal core of ice must be present because: (1) The terminal slopes of the block terraces are as steep as 42°, whereas the normal talus slope of the area is only 30°. This suggests an ice matrix between blocks holds them together and enables them to stand at high angles. (2) A complete gradation from moraine-free fringing glaciers through moraine-veneered fringing glaciers to block terraces exists. (3) Most of the block terraces are adjacent or close to fringing or valley glaciers. (4) The block terraces and the fringing glaciers have approximately the same relationship to the mountain cliffs and about the same thickness and surface gradient.

The block terraces are probably not now moving because: (1) All of them terminate on land, and there are no end moraines in front of them. (2) One has a talus cone with a regular shape and some of the others have normal talus slopes at their upper edges (Fig. 10). (3) They average less than 100 feet thick, and they rest on rather flat slopes (Matthes, 1900, p. 190).

The absence of end moraines also indicates that the terraces have been stagnant since reaching their present boundaries. The volume of the talus which buries the terraces is in part a function of the length of time since they have been stagnant. It appears to be only a fraction of the total time during which talus has been forming in the area.

The block terraces on the northwest side of Roman Four Mountain are, broadly speaking, stagnant remnants of the nearby valley glacier. This is indicated by the proximity of the valley glacier, by the relationship of the block terraces

to the projected profile of the valley glacier, and by the fact that the block terraces slope in the same direction as the valley glacier. The block terraces owe their location to the presence of ravines in the bedrock cliffs immediately above them. More blocks and snow accumulated at the foot of these ravines than elsewhere.

The proximity of the block terraces found elsewhere to fringing glaciers, and their similarity to moraine-veneered fringing glaciers suggest that they are probably the stagnant, shrunken remnants of fringing glaciers.

The relatively flat sloping surfaces of the block terraces prove that the blocks did not reach their positions under present conditions. The blocks are too far from the cliffs to have reached their positions individually under present conditions, and had they been deposited by landsliding under present conditions the surfaces of the terraces would be much more irregular (McConnell and Brock, 1904, p. 9). They must have been brought, therefore, to their present positions at an earlier date by the movement of the fringing and valley glaciers from which the terraces were derived. The margins of the block terrace on Neny Island are somewhat higher than the central portion for the same reason that lateral moraines on glaciers are higher than ablation moraines on the central parts of glaciers.

As deglaciation in this area continues, the ice cores in these block terraces will shrink and the block terraces will decrease in height and will be buried progressively by talus; finally, with the disappearance of the cores, the blocks will be let down as superglacial moraine on subglacial and englacial moraine. Whether a block terrace or a block field finally results will depend upon the thickness of the morainal material, on the height of the terrain beneath the block terraces and on the height of the adjacent areas (Fig. 11). These block terraces are the result of stagnation and are an intermediate stage between actively moving glaciers and ground moraine.

Alluvium

An alluvial fan on the north side of Neny Island is surrounded on three sides by talus and on the fourth by the ocean. It is about 200 feet wide where it terminates along the strand line, and its apex is about 110 feet above sea level. It rests on bedrock, talus, and on both elevated and modern beach deposits. Its fragments are only slightly rounded. Gullies margined by poorly developed levees are found on it. Surface irregularities suggest that some deposition took place on an irregular snow cover (Nichols, 1937, p. 403). The fan owes its existence to a col which is located above the fan and between the two principal peaks of Neny Island. The bottom of the col slopes northward, and the melt water formed in it is therefore funneled downward to the area where the fan is found. This fan was the only significant deposit of alluvium seen by the writer. There is only a very small amount of channeled running water in this part of the Antarctic during the summer, and none during the winter. It does an insignificant amount of geologic work and is of much less importance as a geologic process than ice, waves and shore currents, and talus-forming processes.

Average Thickness of Antarctic Continental Icecap

Considerable data have been collected on the depth of the break in slope of the Antarctic continental terrace. Arctowski (1900a, p. 440) of the Belgica Expedition found it at about 1800 feet in West Antarctica. E. V. Drygalski (*in* Priestley, 1923, p. 58) reported it to be at 2250 feet. The break in slope in the Ross Sea area on a basis of the bathometric data obtained by the Second Byrd Antarctic Expedition, 1933–1935, appears to be at roughly 1600 feet (Roos, 1937, p. 576–581); an analysis of the data published by the U. S. Navy Department Hydrographic Office (1946a; 1946b) indicates that in another part of the Ross Sea it is also in the neighborhood of 1600 feet. It is at approximately 1600 feet on the west side of the Palmer Peninsula (U. S. Navy Dept. Hydrog. Office, 1939). A fathogram Dietz obtained (1952, Fig. 6) in the Indian Ocean sector of the Antarctic at approximately 66°40′S., 73°5′E. shows the break in slope at about 1800 feet; another fathogram obtained by the U. S. S. Currituck on U. S. Navy Operation Highjump, 1946–1947, between 64°13.2′S., 66°45.2′W., and 64°22.7′S., 66°55.9′W., shows it at approximately 1500 feet.

These data indicate that the average depth of the Antarctic break in slope is approximately 1600 feet. The world average depth of the break in slope obtained from thousands of charts covering all parts of the world is 432 feet (Shepard, 1948, p. 143). That of the Antarctic is, therefore, much deeper than the world average, and Shepard (1948, p. 141) believes it is the deepest in the world. Arctowski (1900a,

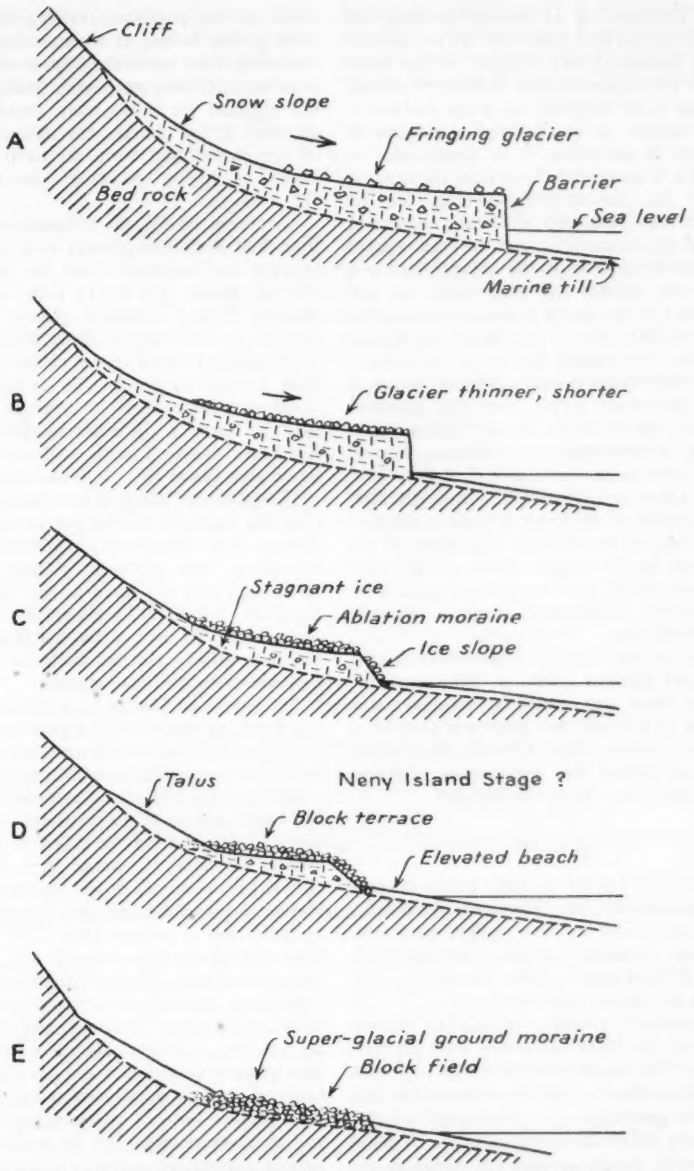

FIGURE 11.—DIAGRAMMATIC SKETCHES SHOWING THE FORMATION OF BLOCK TERRACES

p. 440) was the first to suggest that the great depth of the Antarctic shelf might be due to submergence. Priestley (1923, p. 57–58) believes that the submergence is due to the weight of the existing icecap. Glacial erosion on the shelf and diastrophic movements unrelated to glaciation may also account in part for the great depth.

The thickness of an icecap necessary to depress the earth's crust any given amount can be calculated very roughly. If the great depth of the Antarctic break in slope is assumed to be due to the weight of the icecap and not to glacial erosion or to diastrophic movements unrelated to glaciation; if its depth prior to glaciation is assumed to have been the same as that of the present world average for the break in slope (432 feet); if eustatic changes in sea level due to glaciation and the gravitational distortion of sea level by the icecap, which in a rough way balance out each other, are not considered; if the elastic depression is assumed to be one-fifth that of the plastic depression; if, further, the specific gravity of ice is taken as 0.92, that of the plastic subcrustal material, whose movement away from the glaciated continent caused some of the depression, is taken as 3.5 (Personal communication, Francis Birch), and the present depth of the break in slope is taken as 1600 feet; and if, in addition, the depression of the break in slope is assumed to be equal to the average depression of the crust due to the weight of the icecap; then calculation shows that the average thickness of the Antarctic continental icecap is approximately 3550 feet.

If, on the other hand, it is assumed following Dietz and Menard (1951, p. 1994) that the break in slope was formed by breaker action at about 30 feet and that its present position is due solely to the weight of the ice, then similar calculation shows that the average thickness of the icecap must be about 4800 feet.

Glaciers

More than 75 per cent of the area is covered with permanent ice. Highland, snowdrift, shelf, and island ice and valley, piedmont, tidewater, hanging, cirque, reconstructed, outlet, wall-sided, strand-flat, transection, and fringing glaciers are common.

Highland ice veneers the uplifted erosion surface on the Palmer Peninsula from approximately 63°30′S. to the point where the peninsula joins the mainland, a distance of more than 600 miles. In general, it is between 200 and 300 feet thick (Personal communication, William R. Latady). Small, ice-covered, domal mountains project above the uniformly flat level of the highland ice. In many places the highland ice terminates at the edge of the plateau in a vertical or nearly vertical ice cliff; here great masses of ice occasionally break off and cascade down to the piedmont, valley, cirque, and other glaciers below. At other places where the mountain slope below the edge of the plateau is presumably less steep and, perhaps, where the highland ice slopes more steeply toward the edge of the plateau, the upland ice flows off the plateau and down the steep mountain slopes as highly crevassed outlet glaciers (Pl. 2, fig. 2).

An almost continuous fringe of ice extends from Red Rock Ridge south to Cape Jeremy between the mountains and the strand line (Fig. 3). Where it is fed by valley and outlet glaciers, it is a piedmont glacier. Piedmont glaciers are also present along the east coast of Alexander I Island, north of the shelf ice in King George VI Sound (Pl. 2, fig. 3). The so-called Wordie Shelf ice appears to be in part, at least, a piedmont glacier, and the Northeast Glacier, north and northeast of Stonington Island (Fig. 3), is also one.

The piedmont glaciers have steeper slopes than the highland ice but not as steep slopes as most of the valley, cirque, and cliff glaciers. Commonly these piedmont glaciers push out far enough into the ocean so that large bergs break off. Progressive deglaciation, which has not reduced the area of the highland ice has, however, greatly reduced both the thickness and area of the piedmont glaciers.

The Northeast Glacier has a central zone up and down the glacier which is greatly crevassed. The areas marginal to this zone, however, have only a few narrow crevasses. An area of sea ice everywhere covered with fragments of glacial ice, found in front of the crevassed zone during the cold season, may be called a brash and growler ice delta. It extends from the barrier outward for hundreds of feet and is characterized by an irregular, hummocky topography and by indications of pressure (Fig. 12; Pl. 4, fig. 4). The adjacent barrier is irregular and, in places, collapsed because of the prevalence of crevasses. There is no area of broken glacial ice in front of the marginal zones. The brash and growler ice delta formed as follows: Masses of ice fell from the crevassed barrier onto the sea ice, and ice broke off from the glacial toe and floated upward. The distance between crevasses controlled the size of these masses. The ice which fell was broken by the force of impact into fragments of various sizes. During and following this, the glacier continued to move forward and outward, pushing the ice fragments and sea ice in front of it. Later, another mass of ice fell from the barrier. The continuous forward motion of the gla-

cier pushed this ice outward, while the fragments formed earlier were pushed still farther out; the sea ice beneath the fragments thickened and must have grown progressively thicker floating in open water. The delta appears to indicate a movement of several hundred feet per year for the central zone of the Northeast Glacier. Knowles (1945a, p. 174) found one of

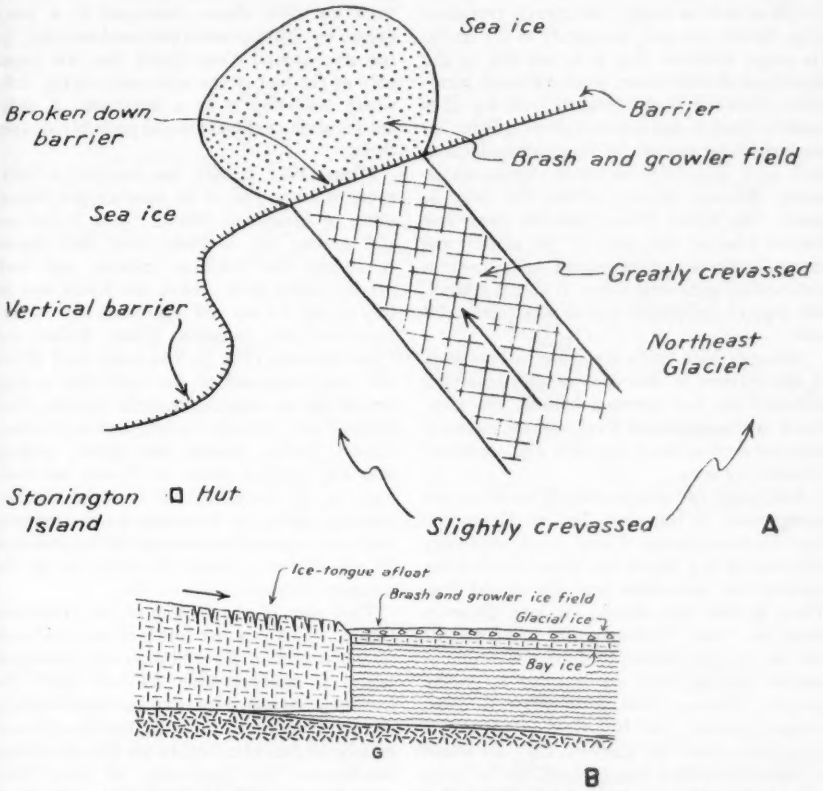

FIGURE 12.—BRASH AND GROWLER ICE FIELD NEXT TO NORTHEAST GLACIER, ANTARCTICA

with increased distance from the barrier. The thrust of the glacier as it moved into the field formed pressure ridges, cracks, and folded bay ice. Where the glacier moved most rapidly, the fragments were pushed farthest out into the bay and the area was widest. The delta was formed, therefore, by a discontinuous collapse of the crevassed barrier and by a rapid, continuous forward motion of the glacier while the barrier remained at essentially the same place. Open water is found along the barrier of the Northeast Glacier during the summer season. The ice delta is, therefore, seasonal. The glacial ice in the outer parts of the delta may have reached its present position in part by the marginal areas of the Northeast Glacier to be moving at an average rate of 0.25 foot per day. Great differential motion exists, therefore, between the rapidly and slowly moving parts of this glacier. Ice deltas are found along the east coast of Alexander I Island and are common in the area north of Stonington Island.

Neny Glacier (Fig. 3), terminating in Neny Fjord, is a greatly crevassed valley glacier. It is approximately 5 miles wide near its terminus and is many times as long (Pl. 1, fig. 3). Some of its many tributaries join it on grade; others hang high above it. The large icebergs breaking off from the southern part of its terminus and the folded bay ice found in front of it in this

area (Pl. 2, fig. 1) prove that it is actively moving.

The north end of Neny Glacier terminates in a transverse ridge tens of feet higher than that part of the glacier immediately upstream. A mile or more in length, this greatly crevassed ridge flattens out and disappears to the south. Its shape indicates that it is not due to the deposition of wind-blown snow, although wind-blown snow has been deposited in its lee. It is unlikely that it has resulted from differential wastage of the glacier, for there are no factors, such as a protective morainal veneer, which would decrease wastage where the ridge is found. The writer thinks that the ridge was formed because this part of the glacier was thrust, by pressure from behind, up and over a pre-existing transverse ridge. If this is correct, this part of the glacier moved as a rigid, solid unit.

Although high cliffs are found above most of the glaciers in this part of the Antarctic, moraines are not common because the snow line is not far above sea level, and the morainal material derived from the cliffs and elsewhere is buried by snow.

Mountains rise almost directly from the sea along much of the coast line of Marguerite Bay. Narrow glaciers of local origin commonly terminating in a barrier are found between the base of the mountains and the strand line. These glaciers may extend for long distances along the coast. Although they are found at the foot of steep slopes, they are not piedmont glaciers because they are not fed by valley glaciers. Fleming (1940, p. 93–98) calls them fringing glaciers, and Holtedahl (1935, p. 22) calls them strand-flat glaciers. They are found on the south side of Neny Island, on the north side of Neny Fjord, on the south side of Red Rock Ridge near its western terminus, and elsewhere. The fringing glacier on the south side of Neny Island is typical of these glaciers. It is about 1 mile long, only a few hundred yards wide, and in places its barrier is 50 feet high.

Their movement is proved by the presence of an occasional bergschrund (Fleming, 1940, p. 93), by the absence of thick ablation moraines on the surfaces of these glaciers, and by the calving which takes place at the barriers. Morainal material veneers some of these fringing glaciers. The ice in the barriers is in general clean, but individual fragments and dirt and fragment layers are present in places. Unconformities and cross-bedding were also seen in the barriers. Beach gravels are found at the foot of some of the barriers, and it seems likely that some of these fringing glaciers have overridden beach gravels because of a lowering of sea level, consequent on deglaciation. These glaciers are fed mainly by snow avalanches from the cliffs above them and to a lesser degree by drifting snow and local snowfall. In the area around Neny Fjord they are found only at the foot of the high south-facing cliffs, where insolation is at a minimum. A slight amelioration of climate would probably destroy them.

Fuchs (1951, p. 405) has recorded a thickening of ice on one of the snow-capped islands south of Mushroom Island. On a 20-foot ice cliff resting on bedrock, two dark layers containing bird feathers, excreta, and rock particles were seen. Above the layers was 50 feet of ice. An ice cliff approximately 30 feet high was seen between Windy Valley and Cape Berteaux (Fig. 3). The lower part of this cliff was composed of ice containing a high percentage of englacial material ranging from blocks 5 and more feet in length down to dust. Closely spaced, parallel dirt bands, arching over and sagging under the blocks, are common in this lower ice. A layer of ablation moraine resting on a surface which truncates the bands is found at the top of this ice. Between 15 and 25 feet of relatively clean ice top the ablation moraine.

That part of the barrier of the Northeast Glacier which is a few hundred feet northeast of the American Base Station on Stonington Island is approximately 40 feet high. The lowermost 30 feet is massive ice which contains faulted blue veins and dirt bands. Approximately 10 feet of stratified ice unconformably overlies it. The significance of these three examples of ice thickening is not understood.

Snowdrift ice is found on Stonington Island and elsewhere. A prominent area of snowdrift ice below the snow line is found in the southeastern part of Stonington Island (Wright and Priestley, 1922, p. 151–152). The area is several hundred feet long and somewhat less in width and is immediately northwest of a line of bedrock knobs aligned northeast-southwest. Five coalescing, smooth, streamlined lobes of snowdrift ice, looking something like plunging anticlines, slope gently away from the bedrock knobs (Pl. 4, fig. 5). This ice pinches out into feather-edged margins on land, and where it reaches the strand line it terminates a short distance above mean sea level in a barrier 10 feet high in places. The crests of the lobes slope N.290°E., between 8° and 14°. The sides

of the lobes have still steeper slopes, and between them are interlobate swales. The snowdrift ice rests on bedrock and on elevated bedrock knobs, have a streamlined shape and decrease in size with increasing distance downwind from the obstacles. They are similar to

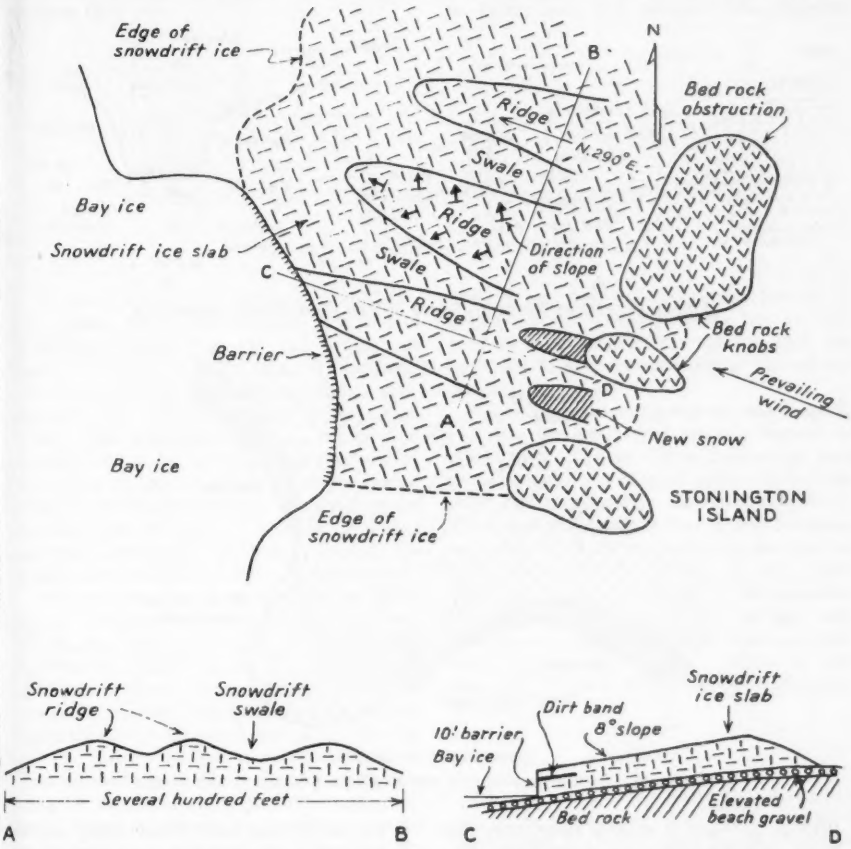

FIGURE 13.—SNOWDRIFT ICE SLAB ON THE EAST SIDE OF STONINGTON ISLAND, ANTARCTICA

beach gravels (Fig. 13). Its thickness and the flatness of the surface on which it rests strongly suggest that it is stationary (Matthes, 1900, p. 190). One prominent dirt band was seen on the barrier, but the blue veins common in glacier barriers are not present. The ice slabs are close to the windward side of the island; much of the ice in them was probably blown as snow from the bay ice.

That they are snowdrift ice slabs is proved by the following: (1) The long axis of each lobe is aligned N.290°E.-N.110°E., and the prevailing wind for the area is southeast (Peterson, 1948a, p. 7). (2) The ice slabs, on the leeward side of the sand shadows formed in back of fixed obstructions (Bagnold, 1942, p. 188–191). (3) Their existence below the snow line. Although the major configuration is due to the accumulation of wind-blown snow on the leeward side of bedrock obstructions, some of the minor slopes and surfaces near the knobs are probably due to radiation from the knobs.

CLIFF AND SNOUT TERMINI

In most places around Marguerite Bay, fringing, valley, cliff, cirque, and piedmont glaciers and shelf ice reach the ocean, forming

the well-known ice cliff or barrier (Pl. 1, fig. 2). The barrier is in most places more or less vertical; it varies considerably in height—in places it is as much as 200 feet high (Fleming, 1940, p. 93)—and it extends along more than 80 per cent of the coast line of Marguerite Bay. The thickness, density, and morainal content of the ice are the most important factors controlling the height in free-floating ice masses. The height of the barrier of a grounded ice mass is controlled by the thickness of the glacier and the depth of the water in which it terminates. The farther out the ice pushes into open water, the lower the barrier is, in general. The position of the barrier is determined by the rate of forward movement of the glacier and the speed with which the barrier is pushed back by the attack of the ocean. The barriers of slow-moving fringing glaciers and nearly stagnant snowdrift ice slabs are not far from the high-tide mark. The more rapidly moving valley and piedmont glaciers push farther out into the ocean, but many of them are also grounded. Glaciers moving still more rapidly may be afloat at their distal end.

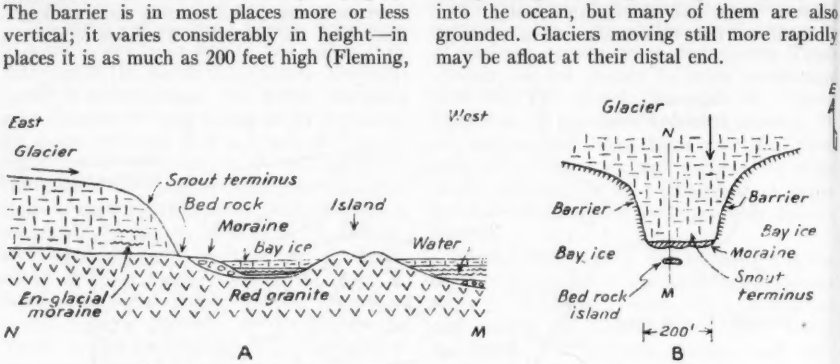

FIGURE 14.—SNOUT TERMINUS SOUTH OF RED ROCK RIDGE, ANTARCTICA

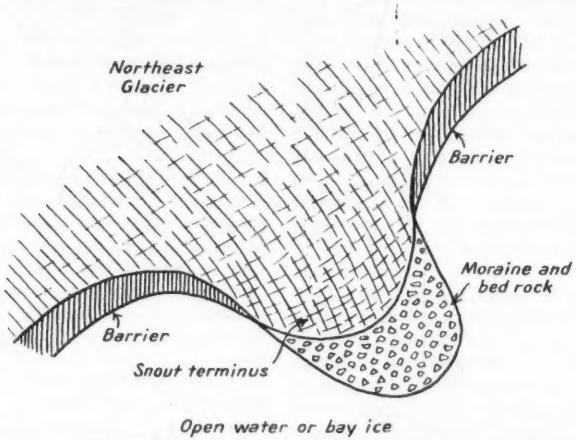

FIGURE 15.—SNOUT TERMINUS OF THE NORTHEAST GLACIER, ANTARCTICA

The barrier is in most places nearly vertical because the ice is melted and worn back more rapidly at sea level than above; the walls of crevasses, which are usually nearly vertical, control calving; and the buoyant action of the water on floating ice sets up stresses which tend to form vertical fractures at the zone where the floating and grounded ice are in contact.

A glacier that does not reach the ocean but stops instead on land terminates in the Marguerite Bay area and elsewhere in a curve convex outward in the "snout" (Wright and Priestley, 1922, p. 259–261; Figs. 77, 78). The snout may be steep or flat. A vertical barrier extends for miles south from Red Rock Ridge. About 2 miles south of Red Rock Ridge, how-

ever, the barrier is replaced for 200 feet by a snout. Investigation showed that a small area of bedrock cropped out above sea level here and that the glacier terminated on the bedrock outcrop (Fig. 14).

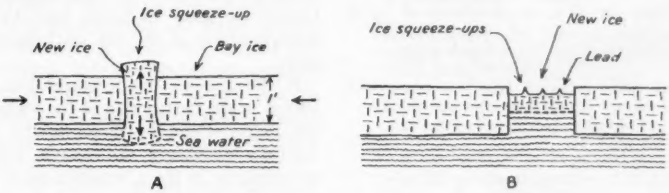

FIGURE 16.—SQUEEZE-UPS FOUND ON BAY ICE

A snout replaces the barrier of the Northeast Glacier for a short distance just east of Stonington Island (Fig. 15); the terminus of Neny Glacier has a snout, and the Northeast Glacier terminates in a snout against a snowdrift ice slab which covers part of Stonington Island. The knowledge that bedrock is commonly found at the foot of a snout was used by the writer to locate bedrock along the barrier coast line of Marguerite Bay. The snouts could be seen from afar, and at their foot, bedrock outcrops, commonly snow-covered and too small to be seen for any distance, were found.

On first thought, it might seem as if the snout terminus were due to extrusion flow (Demorest, 1942, p. 35–37; Seligman, 1947), but this is unlikely because the ice is too thin and the gradients are too steep. The snout terminus probably forms because: (1) There is more ablation in the upper part of the terminus of the glacier because morainal material is concentrated there. (2) If the meltwater running on the surface of a glacier is warmed by solar radiation because the glacier is veneered with moraine, it will, on cascading down the terminus of the glacier, melt more ice higher up on the terminus than lower down. (3) Snow accumulates at the foot of the terminus of the glacier. (4) Ice breaks off from the upper part of the terminus and accumulates at the lower part.

BAY ICE

Squeeze-ups

Ridgelike protuberances of ice standing above the bay ice and located along former cracks were seen a short time after the bay ice had grown thick enough to support a man. These linear ice squeeze-ups were a few inches high, many feet long, and had vertical sides (Fig. 16A). Following the formation of the bay ice, cracks were opened up, new ice was formed in them, and this material was squeezed upward and probably downward because of pressure which developed in the bay ice. The new ice in the cracks was not too hard and rigid, but its sides indicate that it was not too plastic.

Another type of ice squeeze-up was found in the new ice which had recently formed in cracks in the bay ice. These squeeze-ups were wedged-shaped, terminated upward in a sharp edge, and progressively thickened downward. They were a few inches high, a few feet long, and extended from the surface of the new ice up to the level of the old bay ice (Fig. 16B). They may have been formed by compression, as were the other squeeze-ups, or they may have been formed in cracks which progressively widened as water or plastic ice was squeezed upward in them by hydrostatic pressure.

Ponds

The bay ice in Neny Fjord near the south side of the terminus of Neny Glacier has been thrown into a series of open synclinal troughs and anticlinal ridges. They cover hundreds of acres, are roughly parallel to the edge of the glacier, and are cut by cracks; when they were found the bay ice was several feet thick (Pl. 4, fig. 6). The distance from ridge to ridge is 50 feet or more and from crest to trough it is several feet. The wide-open, black-looking cracks which are perpendicular to the folds and to the edge of the barrier are due to tension and/or shear. They have been considerably widened by melting. Similar features have been described by Wright and Priestley (1922, p. 341–354), Gould (1935, Pl. 117, 118), and Poulter (1947, Figs. 3, 4). Sea ice can be folded by the thrusting of glaciers into it, by a sudden

increase in the temperature of the sea ice, and by other less important factors. The distribution and size of the folds under discussion indicate

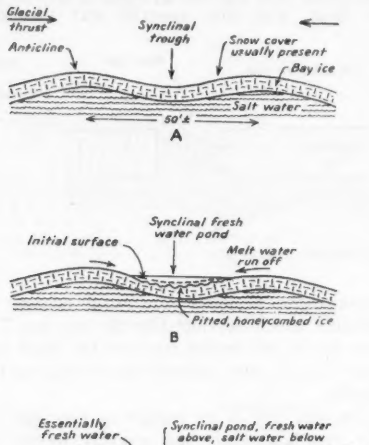

FIGURE 17.—FORMATION OF SYNCLINAL FRESH-WATER PONDS AND SLUSHY SNOW ON BAY ICE

that they are due to the movement of Neny Glacier.

Ponds more than 900 feet long, 20 to 30 feet wide, and several feet deep occupy the synclinal troughs during the summer months before the break-up of the sea ice. They are straight, elongate, and simple in outline, although in places they bifurcate, and ponds in adjoining troughs are connected. Some ponds are connected with the sea water by cracks or thaw holes. Those not connected contain only fresh water; those which are connected have fresh water only at the surface. Apparently in these cases the warm, fresh water floats on the heavier salt water. Figure 17 shows diagrammatic sketches of the formation and development of these ponds. Following the formation of the bay ice, snow accumulated on it, and it was folded owing to the movement of Neny Glacier. With the arrival of summer and periods with the temperature above 32°F. (Peterson, 1948a, p. 7), the snow cover and the sea ice melted. Meltwater collected in the troughs and was heated by solar radiation and by the air; honeycombing of the sea ice beneath it took place.

If the free air temperature alone were involved in the destruction of the folded bay ice, the ridges would be more rapidly destroyed than the troughs, as the troughs, before water accumulated in them, would contain colder air on the average, and the saturated air would not be blown away from the troughs as readily as from the ridges. After the accumulation of the water in the troughs, the ice in them would not be as easily melted by the free air temperature because the water would act as an insulating blanket. The fact that the troughs have been destroyed more than the ridges proves, therefore, that solar radiation and not the free air temperature is the agent mainly responsible for the destruction of the bay ice. The water absorbs solar radiation more readily than does the snow and ice, and the ice in the troughs below the ponds is therefore more rapidly destroyed than that in the ridges.

Slush

A layer of slushy snow was commonly found between the bay ice and the upper, dry snow covering it (Peterson, 1948b, p. 22). Men may break through the upper, dry snow and fall into the slush below. It was sometimes impossible to use weasels on this surface, and the slush at times made it difficult or impossible for planes to take off from the bay ice. This layer of slush was formed in several ways. Anticlines, synclines, and cracks are found in the bay ice close to the barriers of actively moving glaciers. Slushy snow is found in the synclines. It is commonly formed by flooding when cracks are developed in folded, snow-covered bay ice (Fig. 17D). Fortunately, one can avoid this terrain by staying a mile or more from the glaciers. Thin bay ice may be so loaded down by a snow cover that the top of it sinks below sea level. If cracks are present in the bay ice, flooding takes place and a layer of slush is formed. The snow on the bay ice melts at the surface during the late spring and summer months. The meltwater drains downward until it reaches the impervious bay ice. The accumu-

lation of this meltwater on top of the bay ice and at the bottom of the snow cover results in a layer of slush. Slush zones might also be formed after the fall of heavy, wet snow. A layer of slush was found near Stonington Island in May and June 1947, which may be explained as follows: The more quickly salt water freezes, the greater the salinity of the ice. Wright and Priestley (1922, p. 338) showed that the greatest salt content in the bay ice is at and near its upper surface. Ice of high salinity and therefore of low melting point will be formed if the ocean freezes rapidly. If, later, snow falls on this ice, a layer of slush will be formed when the salty upper part of the bay ice melts because of heat received from the ocean or from the atmosphere.

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PENNSYLVANIAN MARINE CYCLOTHEMS IN TENNESSEE

BY CHARLES W. WILSON, JR., AND RICHARD G. STEARNS

ABSTRACT

In contrast to prevailing concepts, Pennsylvanian (Pottsville) sedimentary rocks of Tennessee, except for coals and adjacent strata, are considered herein to have been deposited in marine water of considerable depth.

Blanket sandstones, restricted to the lower third of the column, were deposited by southwestward-moving currents in a shallow (*i.e.* tens of feet deep) arm of the sea, which was greatly restricted by Appalachia to the southeast and the emergent Cincinnati arch to the northwest. Digitate sandstones occur in the upper beds and extend westward partly across the coal field. These digitate sandstones were deposited on the east flank of the Interior Sea where sediment-laden water moved down the slope into deeper water; each tongue may have matched a stream mouth which had its headwaters in Appalachia. At this time the Cincinnati arch was buried. Shale blankets were deposited in deep, quiet water. Widespread coal zones mark periods of abrupt withdrawal of the sea.

On the assumption that the bulk of the strata are marine, the writers have applied the concept of four-phase cyclothem deposition and divided the lower third of the column into five cyclothems. Phase 1 is commonly represented by coal beneath blanket sandstones. Phase 2 is represented by a widespread marine sandstone blanket deposited in shallow water; local coals within these sandstones indicate local filling up of the shallow sea by rapid sedimentation adjacent to Appalachia. Phase 3 is represented by the widespread coal zone in normal position above the blanket sandstones. Phase 4 is represented by a widespread shale blanket deposited in a deep sea. Stratigraphic cross sections and paleogeographic block diagrams illustrate each phase.

CONTENTS

TEXT

	Page
Introduction	1452
Previous investigations	1452
Depositional environments	1452
Cyclothems	1453
Acknowledgments	1453
Stratigraphy	1454
Classification of units	1454
Lithology	1454
Sandstones	1455
Types of sandstones and their distribution	1455
Blanket sandstones of the Gizzard and Crab Orchard Mountains groups	1455
Blanket sandstones of the Crooked Fork group	1457
Digitate sandstones	1457
Occurrences of fossils	1457
Paleogeography	1458
Interpretations of environments	1458
General statement	1458
Blanket sandstones	1459
Shale blankets	1459
Digitate sandstones	1459
Influence of tectonic provinces on Pennsylvanian deposits	1460
Filling of the Appalachian trough and covering of the Cincinnati arch	1460
Cyclothems in the Pennsylvanian of Tennessee	1461
Paleogeography during typical cyclothem events	1462
Phase 1: nonmarine conditions	1462
Phase 2: shallow marine invasion	1462
Phase 3: abrupt withdrawal of the sea	1463
Phase 4: deeper marine invasion	1463
Conclusions	1465
References cited	1465

ILLUSTRATIONS

Figure		Page
1.	Generalized geologic map showing the regional setting of the Tennessee coal field	1452
2.	Generalized stratigraphic section of the lower part of the Pennsylvanian of Tennessee	1454
3.	Distribution of massive, thin, and shaly portions of blanket sandstones	1456
4.	Distribution of massive and thin portions of younger sandstones	1456
5.	Regional structural features in the vicinity of the Tennessee coal field	1460
6.	Generalized paleogeography of marine invasions of Tennessee	1461
7.	A typical cycle in the lower Pennsylvanian of Tennessee considered as a cyclothem	1462
8.	Classification of part of the lower Pennsylvanian of Tennessee as five cyclothems	1463
9.	Geology and physiography of eastern Tennessee during the four phases of a typical cyclothem	1464

Introduction

This paper advances the thesis that the bulk of Pennsylvanian strata in Tennessee is marine. By assuming that Pennsylvanian strata were deposited under the influence of the four-phase cyclic eustatic sea-level change (modified glacial-control theory of Wheeler and Murray, 1957), one can explain many of the details of Pennsylvanian stratigraphy in Tennessee.

It is not the purpose here to review in detail the depositional history of the entire Pennsylvanian column in Tennessee. A few of the better known and most extensive beds are used to illustrate conditions believed to be typical of the various types of strata. These typical situations are illustrated by paleogeographic maps and profiles across the basin of deposition.

The ideas presented here are based largely on reconnaissance and detailed mapping of the Pennsylvanian of Tennessee from 1948 to 1955 by the writers and other personnel of the Tennessee Division of Geology. This work has resulted in a greater knowledge of the relationships of rock units than was possible previously (Wilson, Jewell, and Luther, 1956).

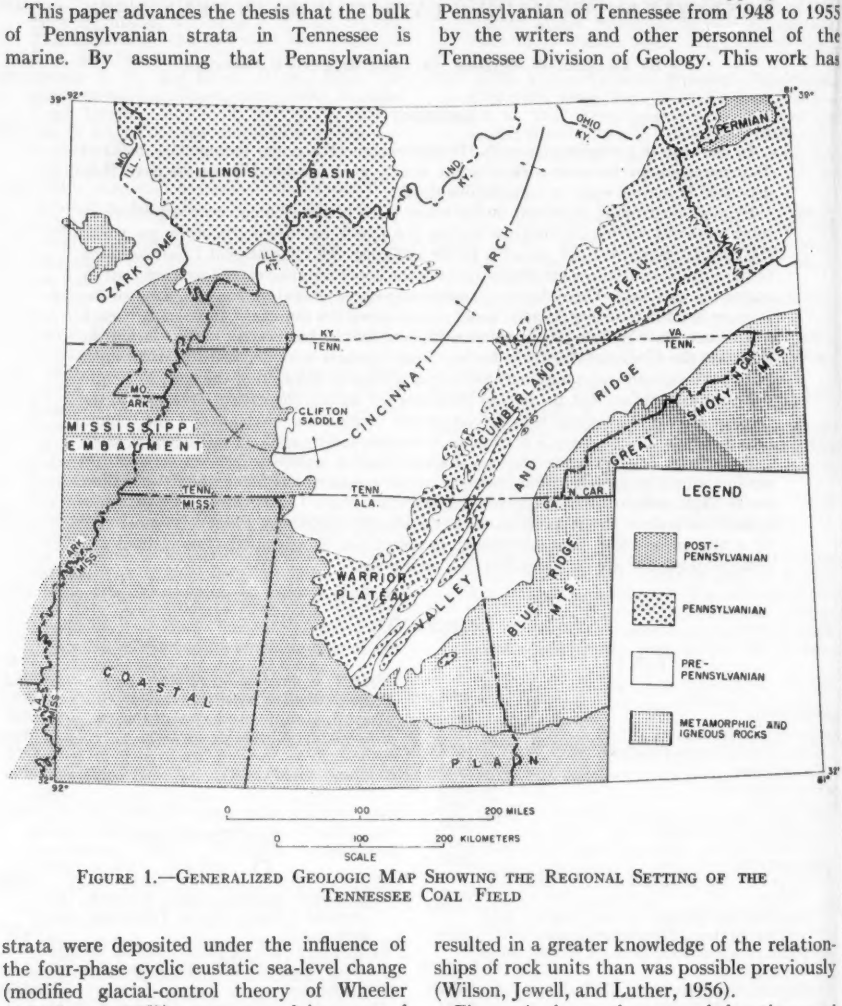

Figure 1.—Generalized Geologic Map Showing the Regional Setting of the Tennessee Coal Field

Figure 1 shows the general location and regional geologic relationships of the Tennessee coal field.

Previous Investigations

Depositional Environments

White (1904, p. 277), discussing the concept of marine deposition in the Appalachian region, stated that "nearly all of the present

Appalachian Coal Measures area bears the marks, either paleontological or stratigraphical, of the continued transgression of the sea" and that the area had "free access to marine animals from the broad end of the trough to the southward at this time." He recognized a restriction of the "Pottsville sea" (p. 274) by the Cincinnati arch, with transgressive encroachment of "beds" up the flank of the arch until "the Pottsville sea swept across the Cincinnati arch in southern Kentucky and Tennessee, so as to connect with the interior region" (p. 281).

Nelson (1925, p. 39) stated that

> "The old Pennsylvanian sea did not at the beginning cover all of the area now occupied by the coal measures. It originally occupied only the eastern and southeastern portions of the area, and from these points advanced westward and northward over the old Pennington land surface. . . . shifting and changing of the coast line of the sea made many erosional unconformities, also the sandstones, shales and coals deposited were variable in character over the region, and in a number of places, striking examples can be seen, where large shale lenses occur in sandstones, or sandstones go out, and are replaced by shale."

Nelson made no further statements concerning marine conditions.

Butts and Nelson (1925) made no reference to environment in the Crossville quadrangle. Glenn (1925) made no interpretations of environments, but he did discuss marine, brackish, and terrestrial faunas and floras. Wanless (1946, p. 126) stated that "The truly marine zones are mostly shales, in some instances associated with a thin band of impure limestone. . . ." He summarized environments of deposition as follows (1946, p. 131–132):

> "A widespread delta plain fronting the sea with a network of delta lakes, marshes, and lagoons and shifting channels of discharge for the streams seems the most likely type of environment. Small changes in sea level would bring about frequent changes in the environment at a particular place from an emergent forested lowland plain to marsh, lake, lagoon, or river channel. All gradations from the fresh water of the river to the normal salinity of the sea might be expected in such an environment."

C. H. Summerson (1942, Ph.D. thesis, Univ. of Illinois) has contributed to the present knowledge of marine and brackish-water invertebrates of the area.

R. M. Mitchum, Jr. (1954, Ph.D. thesis, Northwestern Univ.), concluded that the extensive clean sandstones of Tennessee are marine, but that the intervening shales are nonmarine, with the exception of some of the Whetstone Creek type shales. Mitchum is the only writer since White who has emphasized the conclusion that a significant proportion of Pennsylvanian sedimentary rocks is marine.

Cyclothems

Weller (1930) was the first to point out the significance of Pennsylvanian cyclic deposition, and Wanless and Shepard (1936) were the first to attribute the cycles to glacially controlled eustatic changes in sea level. This latter concept was discussed and revised into a four-phase cycle of eustatic sea-level changes by Wheeler and Murray (1957), to which Weller (1958) took exception.

Workers in Tennessee have heretofore not used the cyclothem concept. Wanless (1946, p. 129), in correlating beds in the upper part of the Pennsylvanian of Tennessee with those in eastern Kentucky and Ohio, concluded:

> "It is evident that the interval constituting this cyclothem of Stout's Ohio section has become very complex in northern Tennessee, and, if it were divided at all into cyclical units, 15 or 20 in Tennessee would necessarily correspond with one in Ohio. The implication is either (1) that sedimentation in Tennessee must have been much more rapid than in Ohio, or (2) that there must be numerous diastems or breaks in Ohio whose presence is not obvious from stratigraphic relations. The writer believes that both relations are true."

However, Wanless does not finally reject the idea for future use as he further states (p. 129):

> "In most parts of the southern Appalachian coal field, however, a sort of rhythmic sequence is frequently repeated . . .It is not proposed that these cyclic units be used now as a basis for classification of the strata of the region, as it seems little would be gained thereby. That the areas of rapid sedimentation should show a type of rhythmic sequence of strata many times repeated, somewhat resembling the rhythm in areas of much slower sedimentation, presents a problem for which no immediate solution is apparent."

Extensive new data and the revised cyclothem concept of Wheeler and Murray are the basis for the present writers' belief that the more extensive and better known portion of the Tennessee Pennsylvanian column represents a sequence of cyclothems.

Acknowledgments

John W. Jewell and Edward T. Luther of the Tennessee Division of Geology and Harry J. Klepser of the University of Tennessee furnished information on fossil localities.

J. Marvin Weller of the University of Chicago and Harry E. Wheeler of the University of Washington read the manuscript and contributed many constructive criticisms but do not necessarily agree with all the conclusions.

Many colleagues engaged in fruitful discussions and critical reading of the manuscript. Among these are W. D. Hardeman, State Geologist of Tennessee; W. B. Jewell of Vanderbilt University; Edward T. Luther, Robert J. Floyd, Robert E. Hershey, and Stuart W. Maher of the Tennessee Division of Geology; and Melvin V. Marcher of the U. S. Geological Survey.

Robert J. Floyd, Principal Geologist of the Tennessee Division of Geology, edited the manuscript.

Stratigraphy

Classification of Units

The lower, sandy sequence of the Pennsylvanian in Tennessee is divided into three groups: Gizzard, Crab Orchard Mountains, and Crooked Fork (Fig. 2). The most prominent sandstones in this thick sequence serve as group boundaries. The upper, shaly sequence is subdivided into six groups, of which only the oldest, the Slatestone group, will be considered. The writers will suggest a cyclothem subdivision of part of this sequence as a useful genetic classification.

Lithology

Pennsylvanian rocks in Tennessee consist almost entirely of water-laid clastic rocks of various kinds. Sandstones and shales predominate, but there are also coals, siltstones, and insignificant thin calcareous and ferruginous concretions.

Strata in the lower portion of the Pennsylvanian in Tennessee generally persist laterally as gross units but are exceedingly variable in detail. In some areas, sandstones, coal beds, and shale units persist over large areas; elsewhere, they change abruptly. As will be illustrated, however, in the case of selected sandstones these abrupt changes are both systematic and meaningful.

Lithologic types are not unique in their sequence position. For example, fine thinly bedded sandstones of similar appearance occur throughout sequences that the writers believe are cyclothems. In spite of this lack of unique lithology, continuity was demonstrated during the investigation of the Pennsylvanian by members of the Tennessee Division of Geology (Wilson, Jewell, and Luther, 1956) who mapped sandstone, shale, and coal units in detail; in some cases strata were traced for several tens of miles.

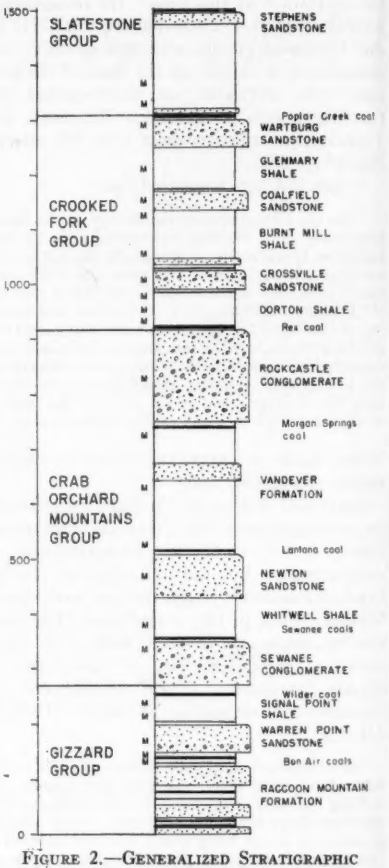

FIGURE 2.—GENERALIZED STRATIGRAPHIC SECTION OF THE LOWER PART OF THE PENNSYLVANIAN OF TENNESSEE

M denotes positions where marine fossils have been found.

The discussion of the various lithologies of Pennsylvanian rocks given in the next few paragraphs is summarized from Wanless (1946, p. 124–128).

Sandstones range from very fine-grained to coarse-grained, but coarse-grained sandstones are uncommon. They are notably quartzose,

but many have enough iron to oxidize them rusty brown. The more massive sandstones commonly rest unconformably on underlying beds, generally with a basal conglomerate of shale or ironstone pebbles. In nearly all cases they grade upward imperceptibly into finer-grained sandstones and then into shale or siltstone, merging with the next higher layers. Aqueous cross-bedding and rounded quartz pebbles are common in the more massive sandstones.

Siltstones resemble sandstone in structure but are finer in texture. When fresh they appear massive, but when weathered they resemble shale. Shale ranges from sandy to silty to well-bedded clay shale. Silty shales commonly display spheroidal weathering, which results in pencillike rectangular splinters that make the strata appear vertical or steeply dipping. All varieties of shale may be light to dark gray, or black, with shades of olive, brown, blue, or green. Dark-gray to black shales commonly contain ironstone as thin bands or flattened oval concretions.

Coals commonly show variability in thickness and extensive splitting, although some are uniform over extensive areas and do not split. Canneloid and splint coals are also present. The coals commonly overlie nonlaminated beds, but they may grade down into laminated shales, siltstones, or sandstones. The underclays may, therefore, be shaly, silty, or sandy. Root traces are common in the underclays.

Sandstones

Types of sandstones and their distribution.—"Massive" sandstone is here defined as thicker than 20 feet, quartzose, massively bedded, prominently cross-bedded, and usually medium- to coarse-grained. "Thin" sandstone is defined as being less than 20 feet thick, fine-textured, thinly bedded and slabby, commonly shaly, and rarely cross-bedded.

"Massive" sandstone is commonly distributed as widespread blankets or digitate masses. "Massive" sandstones of the lower sandy portion of the Pennsylvanian, which includes the Gizzard, Crab Orchard Mountains, and Crooked Fork groups, have a blanket pattern, whereas those of the upper shaly portion of the Pennsylvanian, which includes the Slatestone and younger groups, are digitate. "Massive" portions of blanket sandstones are generally more quartzose than the "massive" fingers of the digitate sandstones.

The blanket sandstones characteristically maintain a thickness of 100 feet or more and have southwest-dipping cross-beds (R. M. Mitchum, Jr., 1954, Ph.D. thesis, Northwestern Univ.). The most extensive blanket sandstones are the Warren Point sandstone of the Gizzard group and the Sewanee, Newton, and Rockcastle conglomeratic sandstones of the Crab Orchard Mountains group. These occur throughout the Cumberland Plateau of Tennessee. Except for the Rockcastle, they pinch out to the northwest, and, except for the Newton, they contain one or more local shaly "splits". The Crossville and Wartburg sandstones of the Crooked Fork group have most of the features of older blanket sandstones but differ in being developed on the west side of the coal field and pinching out eastward. They have been eroded away except in the northern half of the Cumberland Plateau in Tennessee. The writers regard each of these sandstone blankets as the predominant member of the lower portion of a cyclothem.

Digitate sandstones include the Coalfield sandstone of the Crooked Fork group and all sandstones in the younger groups. They form fingers of "massive" sandstone extending northwestward across the coal field. Between and beyond the fingers are persistent "thin" fine-grained sandstone equivalents. Virtually all sandstones in these upper groups have this pattern. The digitate sandstones are not considered to be basal cyclothem members.

Blanket sandstones of the Gizzard and Crab Orchard Mountains groups.—Figure 3A shows the preserved distribution pattern of the Sewanee conglomerate. The patterns of the Warren Point and Newton sandstones are almost identical to that of the Sewanee and are therefore not reproduced here. The Sewanee conglomerate is a blanket of clean quartzose conglomeratic sandstone about a hundred feet thick over most of the coal field. The sand abruptly interfingers with shale to the northwest. In the northwest part of the area, only a thin, fine-grained carbonaceous, micaceous sandstone was deposited. The abrupt interfingering of shale and sandstone has been widely accepted as subsandstone channeling; a "classic" example is apparent channeling at the base of the Sewanee conglomerate on U. S. Highway 70-S, 2 miles west of Bon Air. Local scour does occur along abrupt pinchouts, but laterally along the pinchout line interfingering becomes less abrupt. Details of this less abrupt interfingering may best be seen in the strip pits

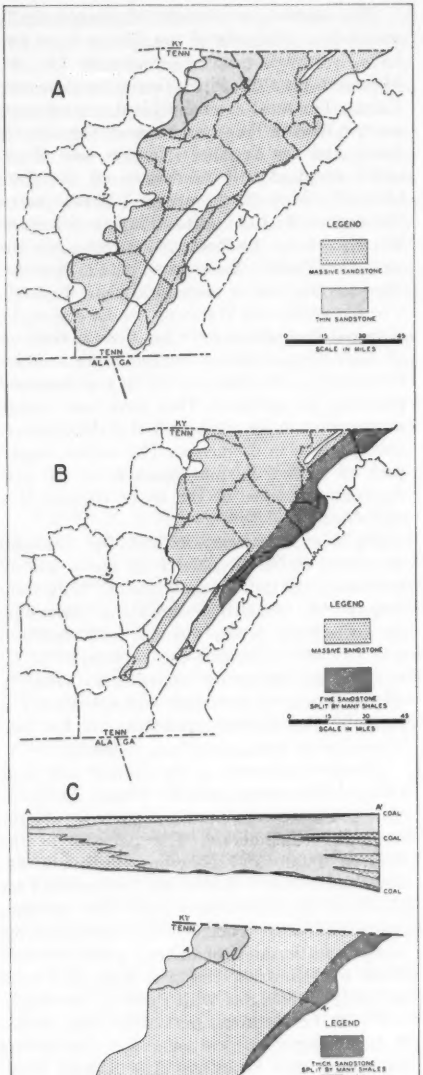

FIGURE 3.—DISTRIBUTION OF MASSIVE, THIN, AND SHALY PORTIONS OF BLANKET SANDSTONES

A, Sewanee conglomerate; B, Rockcastle conglomerate; C, typical blanket sandstone restored by combining patterns of A and B.

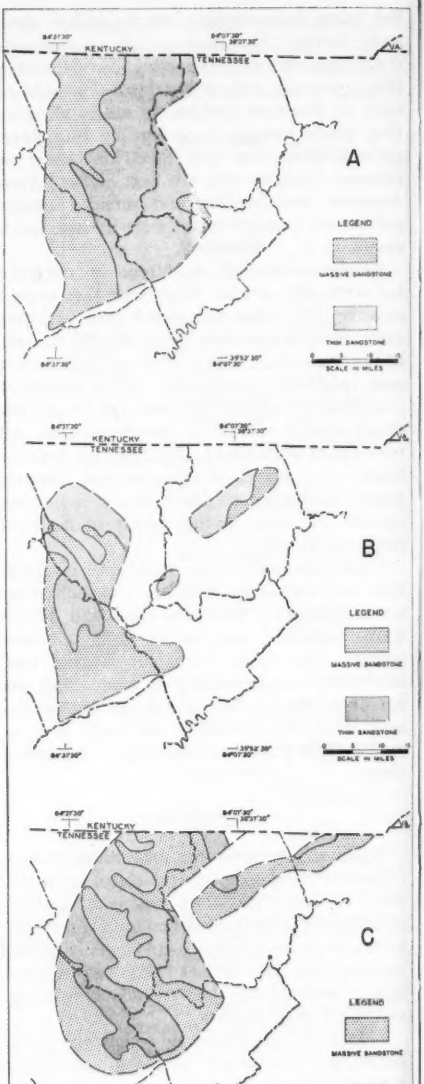

FIGURE 4.—DISTRIBUTION OF MASSIVE AND THIN PORTIONS OF YOUNGER SANDSTONES

A, Wartburg sandstone; B, digitate Coalfield sandstone; C, digitate Stephens sandstone. This pattern is typical of all younger sandstones.

along Looper Branch in the west-central part of the Clarkrange quadrangle, which was mapped in detail along with three adjacent quadrangles (Wilson, 1956). Here, basal beds of the Sewanee conglomerate interfinger with shale through a lateral distance of about a hundred feet rather than a few feet, as they do along the highway west of Bon Air.

Figure 3B shows the preserved distribution pattern of the Rockcastle conglomerate. This is a thick blanket throughout the coal field, even in the northwest area where the underlying sandstones are thin. On the east border of the coal field, however, the Rockcastle thickens and splits into several units of alternating clean sandstone and carbonaceous shaly beds. The shaly beds contain coal.

The present coal field is a linear belt containing only remnants of the original depositional units. To visualize the paleogeography during deposition, one must consider what the pattern was like beyond the present area of preservation. This is done, in part, by analogy between adjacent sandstone beds. That is to say, a facies change observed in one sandstone also may have occurred in the same direction in an adjacent sandstone, but beyond the present erosional limits of the coal field.

Figure 3C is a restoration of a typical older blanket sandstone derived by combining the westward pinchout of the Sewanee conglomerate (Fig. 3A) with the eastward thickening and shale inclusions of the Rockcastle (Fig. 3B).

Blanket sandstones of the Crooked Fork group.—On the west side of the coal field the Crossville and Wartburg sandstones (Fig. 4A) are similar lithologically to the older blanket sandstones. Eastward they abruptly pinch out, and a thin fine-grained sandstone continues to the eastern edge of the coal field.

Digitate sandstones.—The Coalfield sandstone, which lies between the Wartburg and Crossville blanket sandstones, has the digitate distribution pattern with fingers of thick sandstone extending westward across the Plateau (Fig. 4B). Between and beyond these "massive" fingers is a "thin" sandstone similar to the thin equivalents of the blanket sandstones. The digitate pattern of the Coalfield sandstone is typical of all sandstones above the Crooked Fork group; a typical example of the Slatestone and younger groups is the Stephens sandstone (Fig. 4C).

Occurrences of Fossils

Marine invertebrates are known from both sandstones and shales in Tennessee. Except for stems and fragments, plants are restricted to beds within and closely adjacent to coal zones. The writers believe that with the exception of these coal-zone beds both the sandstones and shales are marine, and that the stems and plant fragments found in the mass of sandstones and shale did not grow there but were floated in and deposited in open water. Well-preserved land-plant remains have been reported from deep marine environments in several places (Bruun, 1957, p. 650).

Marine fossils have been found in all lithologic units except coal zones. They are relatively abundant in dark coarsely concretionary shale and in "thin" sandstone equivalents of blanket sandstones on the western border of the coal field. Here the fauna is varied and includes trilobites, crinoids, brachiopods, pelecypods, and gastropods. Fossils, either marine or nonmarine, are rare in typical silty to sandy shale, but pelecypods and gastropods may be found if one searches diligently. Marine fossils are extremely rare in the main thick quartzose blanket sand; only two specimens, a poorly preserved productid and part of a crinoid stem, are known. This is not surprising because quartzose sandstones are generally unfossiliferous. Except for these two specimens, logs, seeds, and "problematica" are the only other fossils in the blanket sandstones. The writers believe that these logs and seeds were transported into the area by currents and that these sandstones are, for the most part, marine.

Sandy shale and fine-grained sandstone commonly contain borings and various "problematica" such as *Taonurus caudagalli* which is common in Devonian, Mississippian, and Pennsylvanian marine sandstones. Some markings appear to be very poorly preserved pelecypods or brachiopods. Molds or borings are commonly associated with the marine fossils, and because of this the writers believe that such borings, even when not associated with other fossils, indicate marine deposits.

The close association of brackish- and freshwater fossils noted by Wanless (1946), Scott and Summerson (1943), and C. H. Summerson (1942, Ph.D. thesis, Univ. of Illinois) probably represents the brief interludes when the sea was invading a swamp or retreating.

Well-preserved fronds, *Stigmaria*, and root fossils occur only in and adjacent to coal zones. Nondescript plant debris found along bedding planes of the typical silty shale also occurs with marine fossils, and the writers believe that such material was transported.

Even though Pennsylvanian rocks in Tennessee and in other adjacent areas of the Appala-

chian coal field have been mapped and studied in considerable detail, they have not been adequately examined for fossils. This is probably largely due to the unwarranted assumption that most of these beds are nonmarine, hence barren of fossils.

The following is a list of marine-fossil localities in the lower Pennsylvanian of this report (*See* Fig. 2). Where not otherwise specified, the localities were discovered by the writers. They are listed in stratigraphic order from youngest to oldest.

Slatestone group

Lowest shale member (between the Poplar Creek coal and the Stephens sandstone)
Upper portion of the shale on State Highway 62 east of Coalfield, Morgan County
Near the middle of the shale, 4 miles north of Peabody, Campbell County (Wanless, 1946, Pl. 32, LL.-10)
Not far above the Poplar Creek coal (Wanless, 1946, Pl. 32, LL.-10)
Immediately above Poplar Creek coal, at the west end of Little Brushy Mountain near Wartburg, Morgan County, and in the pits at Robbins, Scott County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collections 11, 12)

Crooked Fork group

Wartburg sandstone, at Coalfield, Morgan County
Glenmary shale, near the middle, along State Highway 62 just east of Coalfield, Morgan County
Coalfield sandstone, on McFarland Creek 2 miles east of Glenmary (C. W. Wilson, Jr., and Robert L. Wilson)
Burnt Mill shale, just above Crossville sandstone, at Potters Falls about 2 miles southeast of Wartburg, Morgan County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 7)
Crossville sandstone, just northwest of Oliver Springs, Anderson County
Dorton shale, just above Rex coal, U. S. Highway 70 east of Ozone, Cumberland County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 2)
Dorton shale, near Potters Falls coal, Potters Falls, Morgan County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 3)
Dorton shale, south of Little Brushy Mountain on the east side of Crooked Creek, Morgan County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 4)
Dorton shale, 2½ miles west of Oakdale, Morgan County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 5)
Dorton shale, on U. S. Highway 27, 7 miles south of Wartburg, Morgan County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 6)
Dorton shale, 25 feet above Rex coal, U. S. Highway 25W, 6 miles northeast of LaFollette, Campbell County (C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 10)

Crab Orchard Mountains group

Rockcastle conglomerate, shale break associated with the Nemo coal near middle of conglomerate, on the west side of Crab Orchard Cove, Cumberland County (John W. Huddle and others)
Vandever formation, just below the Morgan Springs coal, near the University of Tennessee summer camp, Rhea County (Harry J. Klepser)
Vandever formation, just below the Morgan Springs coal, at DeRossett, White County (John W. Jewell)
Vandever formation, just below sandstone near middle of formation, west of Graysville, Rhea County (Wanless, 1946, Pl. 21, AA-15)
Vandever formation, just above the Lantana coal, on the west side of Grassy Cove, Cumberland County (R. G. Stearns and John W. Jewell)
Top of Fentress shale (Vandever equivalent) in ironstone concretion, north of Hanging Limb in Norrod Hollow, Fentress County
Newton sandstone at Clifty, Cumberland County, and DeRossett, White County (John W. Jewell)
Whitwell(?) shale equivalent in the Fentress formation, northwest of Jamestown, Fentress County (Wanless, 1946, Pl. 24, DD-16)
Sewanee conglomerate both in massive sandstone and thin equivalent, half a mile south of Obey City, Overton County

Gizzard group

Signal Point shale at Bon Air, White County Wanless, 1946, Pl. 24, DD-10)
Warren Point sandstone at Bon Air (E. C. Dapples, E. T. Luther, and John W. Jewell)
Raccoon Mountain formation, above Upper Bon Air coal, east of Cane Creek, Van Buren County (Wanless, 1946, Pl. 27, GG-3)
Raccoon Mountain formation, between Bon Air coals, Bon Air, White County (Wanless, 1946, Pl. 24, DD-10; C. H. Summerson, 1942, Ph.D. thesis, Univ. of Illinois, collection 224)

PALEOGEOGRAPHY

Interpretations of Environments

General statement.—Conventionally, most Pennsylvanian strata in Tennessee have been assumed to be nonmarine or transitional, with relatively rare thin marine zones. Dominant conditions are supposed to be transitional. "Transitional" apparently has been intended to mean deposition on a coastal plain in generally brackish or fresh water. Two facts have supported the concept that most of the strata are

transitional or nonmarine: (1) recurrence of obviously nonmarine coals throughout the section, and (2) scarcity of marine fossils. Because of the general absence of fossils, Pennsylvanian strata have been assumed to be almost entirely nonmarine without serious question.

The question of the relative amount of sea-level change that occurred to change deposition from nonmarine to marine arises. Several extensive coals are closely overlain by widespread zones of abundant marine fossils. This has led to the prevailing view that most Pennsylvanian beds were deposited at tide level and that *slight* sea level change would serve to change conditions from marine to transitional.

Recent discoveries of marine fossils in many Pennsylvanian sandstones and shales previously thought to be nonmarine have caused the writers to entertain the idea that most Pennsylvanian strata are marine. Also, the similarity of lithologic sequences in Tennessee to cyclothems described by Wheeler and Murray (1957) in the Western Interior basin suggests that periodic abrupt *marked* sea-level changes controlled sedimentation.

Wheeler and Murray (1957, p. 1985) interpret the cyclothem as representing two transgressions and summarize their views as follows:

"...an appreciable number of typical Pennsylvanian cyclothems in widely separated areas manifest the four following rapid, eustatic, base-level reversals superimposed on a simple tectonic environment of continuous slow subsidence.

1. *Base-level strongly down;* maximum marine withdrawal and regional sub-aerial erosion (channeling); local peat near receded shoreline.
2. *Base-level moderately up;* moderate marine advance; resumption of marine sedimentation basinward (*e.g.*, Western Interior) and initiation of fluvial deposition landward (*e.g.*, Eastern Interior).
3. *Base-level moderately down;* marine withdrawal again to lowest position, but relief insufficient for significant erosion; low, vegetated surface decomposed (underclay) as it slowly subsides into swamp (widespread peat).
4. *Base-level strongly up;* maximum marine advance; marine deposition resumed basinward (Western Interior) and initiated landward (Eastern Interior) in upper hemicyclothem..."

The present writers believe that "Tennessee" can feasibly be substituted for "Western Interior" in the Wheeler and Murray summary. Applying these concepts, the present writers predicted zones or beds where marine fossils would be found and plant fossils would not be found. Several new marine fossil zones were thereby discovered, and beds that were predicted to be barren yielded only plant fragments and films that were not deposited *in situ*. These discoveries, predicted from analogy of Tennessee sequences with those of marine cyclothems of the Western Interior, strengthen both the idea that the bulk of Pennsylvanian strata in Tennessee is marine and that large, abrupt, glacially caused sea-level changes controlled the succession of depositional environments.

The main unit types include coal zones, blanket sandstones, shale blankets, and digitate sandstones. All the types except coal are believed to be marine.

Blanket sandstones.—Marine fossils in blanket sandstones and in the thin equivalent sandstone beds of the Gizzard and Crab Orchard Mountains groups prove that these rocks are marine. Local coals in shale "splits" on the eastern edge of the coal field indicate that these sandstones were deposited in shallow water, at least on the east side of the trough and adjacent to the coals. Cross-beds, which generally dip south and west parallel to the facies changes (R. M. Mitchum, Jr., 1954, Ph.D. thesis, Northwestern Univ.), result from consistent southward currents. The consistent southwest dip of cross-beds, together with a northward increase in size and concentration of pebbles in the Rockcastle, Crossville, and Wartburg, show that, for the most part, these sands had their source an unknown distance northeast of the Tennessee coal field.

Shale blankets.—Marine fossils are most abundant in shale blankets, so that the interpretation that these units are marine is founded on more information than the interpretations of sandstone environments. More finely laminated sedimentary rocks probably indicate deeper water than do the coarse, massively bedded blanket sandstones. Also, as will be shown in a section on cyclothems, analogy of position with the upper shaly portions of Western Interior cyclothems leads the writers to interpret shale as having been deposited in considerably deeper water than the blanket sandstones.

Digitate sandstones.—Fingers of the digitate sandstones are not separated as terrestrial stream-channel fills probably would be. Each finger is connected by a thin sheet of fine-grained sandstone. These thin sheets of fine sandstone are lithologically similar to the thin marine fossil-bearing sandstones that are equivalent to the older blanket sandstones. Apparently, then, these digitate sandstones are subaqueous deposits. The writers believe that they mark submarine distributaries down which sediment-laden water moved from shallow

to deeper water. Perhaps the mouth of a stream flowing from adjacent Appalachia matched each finger.

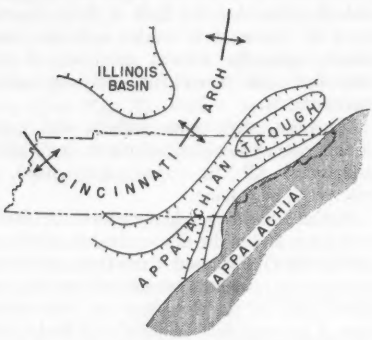

FIGURE 5.—REGIONAL STRUCTURAL FEATURES IN THE VICINITY OF THE TENNESSEE COAL FIELD

Influence of Tectonic Provinces on Pennsylvanian Deposits

Although marked abrupt sea-level changes are visualized as the main control of Pennsylvanian deposition, tectonic movements also left their mark. Figure 5 shows the main structural elements of the region.

The Appalachian trough was topographically low, thus often occupied by the sea (Fig. 6A), and because of downsinking it was the site of deposition of the thickest sediments. Appalachia is drawn as a highland a short distance east of the trough in the present site of the eastern Valley and Ridge province and Smoky Mountains. The exact position of Appalachia is hypothetical, but it is inferred from the prominent tongues of digitate sand that obviously had an eastern source and the intercalations of nonmarine coal zones to the east. The Cincinnati arch formed the west side of the trough. Progressively thicker sediments were deposited southeastward down the flank of the arch, and beds progressively overlap the arch northwestward until in Eastern Kentucky the Wartburg (Corbin) sandstone rests upon Mississippian rocks (Chabot Kilburn, personal communication). These strata reappear west of the arch in the Illinois basin where beds older than the Sewanee coal equivalent (Battery Rock coal) occur (Wanless, 1946, p. 26, 29).

Periods of high sea level were universal, so that when the trough was occupied by an arm of the sea, the Interior region was also flooded. Because it stood higher, the Cincinnati arch was a barrier separating these bodies of water during deposition of older Pennsylvanian beds in Tennessee.

During a period of rising or high sea level, flooding seas aided by trough downsinking caused transgression, but these factors were opposed by rapid deposition on the east side of the trough adjacent to Appalachia. Here adjacent to the highland source, the sea was literally filled up. Such depositional lands were ordinarily restricted to the east side of the trough, but at other times they may have extended a considerable distance westward (shown as a coastal plain on Fig. 6A).

The marked difference in aspect between strata in the Appalachian trough and the interior region with its "typical" cyclothems was caused by the structural setting. The high bordering elements restricted the sea, and Appalachia to the east furnished large supplies of detritus. Deposition and rapid burial ensued in the subsiding trough. Because so much of the sediment was locally derived and rapidly buried, the marine environment left a minimum impression. In addition, heavy runoff from adjacent land areas may have caused considerable dilution of the limited volume of sea water in the trough, making it inhospitable to many marine invertebrates even though continuous open waterways connected it with the sea to the south.

Filling of the Appalachian Trough and Covering of the Cincinnati Arch

During deposition of the older blanket sandstones of the Gizzard and Crab Orchard Mountains groups, the Appalachian trough was the site of an arm of the sea between Appalachia, the highland to the southeast, and the low barrier formed by the Cincinnati arch to the northwest. Currents carried great quantities of sand southwestward along this trough, which accumulated to form the Warren Point, Sewanee, Newton, and Rockcastle conglomeratic sandstones (Fig. 5). This general pattern also continued during deposition of the Crossville sandstone, which, in part, is comparable to older sandstones but differs in that it is developed as a thick mass farther west.

Overlap of the Cincinnati arch is visible in Tennessee in the case of the Warren Point and Sewanee conglomerates. In eastern Kentucky, Chabot Kilburn (Personal communication) reports similar overlap of younger strata. It is a considerable coincidence that beginning of deposition of digitate sandstones and termination of blanket sandstone deposition in Tennes-

see should begin at the approximate horizon where the arch appears to have been buried by sediments in Tennessee. The single case of alternation between blanket and digitate sandstones occurs where the oldest digitate sandstone, the Coalfield, occurs below the youngest blanket sandstone, the Wartburg. The writers interpret this to mean that the arch was temporarily buried during deposition of the Coalfield digitate sandstone, then was uplifted and stripped of sediments temporarily before deposition of the Wartburg blanket sandstone.

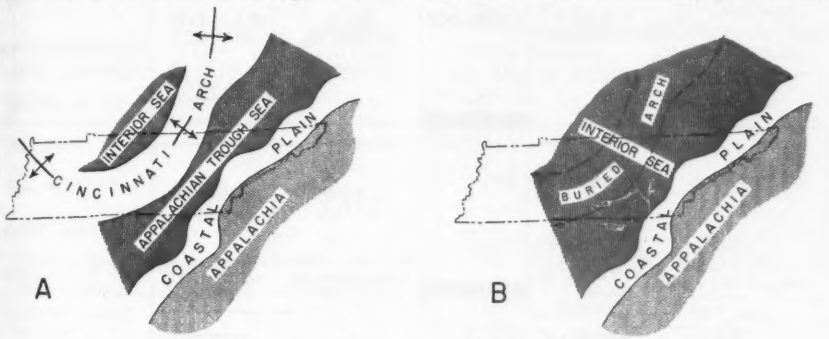

FIGURE 6.—GENERALIZED PALEOGEOGRAPHY OF MARINE INVASIONS OF TENNESSEE

A, during deposition of the lower part of the Pennsylvanian; B, after burial of the Cincinnati arch.

After deposition of the Wartburg, the Cincinnati arch was again buried beneath a cover of sediment for the remainder of Pennsylvanian time (Fig. 6B). All deposition subsequent to that burial of the arch was under control of the adjacent parts of Appalachia, all subsequent sandstones being digitate sands that were locally derived from that land to the east.

This interpretation of sandstone relationships to the arch does not mean that the arch was not submerged by water earlier during shale deposition. The writers believe that shale blankets were deposited in considerably deeper marine water than the sandstone blankets so that the Cincinnati arch was probably submerged beneath the sea (but not "permanently" buried by sediments) several times before deposition of the Wartburg.

CYCLOTHEMS IN THE PENNSYLVANIAN OF TENNESSEE

In the lowest third of the Pennsylvanian column in Tennessee, the clean, quartzose sandstone blankets alternate with shaly blankets in cycles. These begin (arbitrarily) with a coal beneath a blanket sandstone which has no more than a slight basal unconformity. Close above the blanket sandstone is a widespread coal, and above the coal is a shaly unit which contains varying proportions of sandstone. Another coal zone is commonly present close beneath the next blanket sandstone (Fig. 7). This cycle differs from the typical cyclothem of the Eastern Interior basin in three ways: (1) an extra coal occurs beneath the basal sandstone, (2) there is little or no basal channeling beneath the basal sandstone, and (3) the basal blanket sandstones are marine in Tennessee.

The cycle in Tennessee agrees with and is explained by the theory that Pennsylvanian cycles are controlled by eustatic changes in sea level. This theory was first proposed by Wanless and Shepard (1936) and was recently revised and exemplified by Wheeler and Murray (1957) who proposed four phases including two unequal eustatic rises of sea level per cycle.

According to Wheeler and Murray, the typical cyclothem of Illinois changes seaward in three major aspects: (1) a second coal appears at the position of the unconformity beneath the basal sand, (2) the basal unconformity diminishes, and (3) the lower part of the cycle that includes the basal sand changes from nonmarine to marine.

Because cycles in the lower Pennsylvanian in Tennessee fit these changes, the Tennessee cycles may be interpreted as four-phase cyclothems, and the Tennessee coal field may be interpreted as having occupied a seaward position during deposition of lower Pennsylvanian beds. Figure 8 is a classification of the portion of the Pennsylvanian containing the blanket sandstones into five cyclothems. It summarizes the relationships of the cyclothems to named stratigraphic units and the geographic

conditions attending the marked sea-level changes.

At the beginning of each cyclothem (phase 1), the coal field was entirely above sea level; after this an abrupt flooding occurred as a shallow sea occupied the Appalachian trough (phase 2). Then the sea abruptly withdrew (phase 3). Still later another abrupt flooding occurred as a considerably deeper sea occupied the trough (phase 4) and submerged large areas of Appalachia and most if not all of the Cincinnati arch. The sea again abruptly withdrew to complete the cycle.

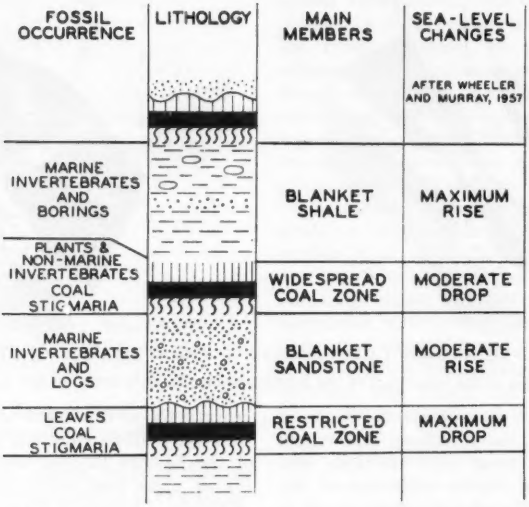

FIGURE 7.—A TYPICAL CYCLE IN THE LOWER PENNSYLVANIAN OF TENNESSEE CONSIDERED AS A CYCLOTHEM

The upper part of the Tennessee Pennsylvanian column has not been subdivided into cyclothems. At present this is not feasible because blanket sandstones are not developed there. However, lithologies of the upper beds are similar to lithologies of lower beds so that they also probably were, except for coal zones, deposited in a relatively deep sea under the influence of alternate flooding and withdrawal of the sea.

PALEOGEOGRAPHY DURING TYPICAL CYCLOTHEM EVENTS

Phase 1: Nonmarine Conditions

The sea withdrew, leaving the old sea floor a wide swamp valley. There, peat accumulated in a swamp over newly buried marine muds of phase 4 of the preceding cyclothem. This coal corresponds with the basal unconformity of a typical cyclothem in the Illinois basin. Paleogeography for this event is essentially similar to phase 3. Phase 1 ended as sea level rose and a shallow sea occupied the Appalachian trough. (*See* Fig. 9).

Phase 2: Shallow Marine Invasion

Blanket sandstones characteristic of the lower Pennsylvanian in Tennessee mark shallow marine invasions and are predominant in the lower portion of cyclothems. The restored older blanket sandstone of the Crab Orchard Mountains group (Fig. 3C) is an example. Over most of the present site of the coal field there was an agitated open sea only a few tens of feet deep with a sand bottom. The west side was slightly deeper with a fine sand or mud bottom. Increased water depth there resulted from a lesser rate of sedimentation far from Appalachia. To the east, adjacent to Appalachia, a subsiding coastal plain was intermittently built out into the structural basin and maintained by more rapid sedimentation adjacent to Appalachia in spite of subsidence and rise of sea level. The Cincinnati arch was a barrier separating the Appalachian Seaway from the Interior Sea.

The pattern of deposition of younger blanket

sandstones of the Crooked Fork group (not illustrated) was essentially similar to that of the older sandstones. All the present area of the coal field was open sea. To the west was a shallow agitated sea with a sand bottom; to the east was deeper water and a mud bottom; then, the structural trough was topographically low, perhaps because sediment supply from Appalachia to the east diminished. At this later time the Cincinnati arch was a lower and narrower strip of land, partly buried during deposition of older strata.

Sands deposited during phase 2 in Tennessee correspond with the basal sandstone portion of a typical cyclothem of the Illinois basin. (*See* Fig. 9).

Phase 3: Abrupt Withdrawal of the Sea

Following deposition of blanket sandstones the sea abruptly withdrew. The old sea bottom again became a wide swampy valley with almost no relief, and widely developed postblanket-sand coal was deposited. A similar paleogeographic situation is visualized for each of the 20 or so widespread coals of the Tennessee coal field. This coal (or coal zone) corresponds with the coal zone of the typical cyclothem of the Illinois basin (*See* Fig. 9).

Phase 4: Deeper Marine Invasion

The sea again rose to abruptly drown the swamps. Deepest water of the cycle occurred as

STRATIGRAPHIC UNIT NAMES	LITHOLOGY	MAIN CYCLOTHEM MEMBERS	SEA-LEVEL CHANGES (After Wheeler and Murray, 1957)	GEOGRAPHIC CONDITION IN THE APPALACHIAN TROUGH
WARTBURG SS				
GLENMARY SH.		BLANKET SHALE	(4) MAXIMUM RISE	DEEP SEA
COALFIELD SS				
BURNT MILL SH.				
Hooper coal		COAL	(3) MODERATE DROP	SWAMPS
CROSSVILLE SS		BLANKET SANDSTONE	(2) MODERATE RISE	SHALLOW SEA
Potters Falls coal		BASAL COAL AND UNCONFORMITY	(1) MAXIMUM DROP	SWAMPS AND EROSION
DORTON SHALE		BLANKET SHALE	(4) MAXIMUM RISE	DEEP SEA
Rex coal		COAL	(3) MODERATE DROP	SWAMPS
ROCKCASTLE CONGLOMERATE		BLANKET SANDSTONE	(2) MODERATE RISE	SHALLOW SEA
Morgan Springs coal		BASAL COAL AND UNCONFORMITY	(1) MAXIMUM DROP	SWAMPS AND EROSION
		BLANKET SHALE	(4) MAXIMUM RISE	DEEP SEA
Lantana coal		COAL	(3) MODERATE DROP	SWAMPS
NEWTON SS		BLANKET SANDSTONE	(2) MODERATE RISE	SHALLOW SEA
		BASAL UNCONFORMITY	(1) MAXIMUM DROP	EROSION
WHITWELL SH.		BLANKET SHALE	(4) MAXIMUM RISE	DEEP SEA
Sewanee coals		COAL	(3) MODERATE DROP	SWAMPS
SEWANEE CONGLOMERATE		BLANKET SANDSTONE	(2) MODERATE RISE	SHALLOW SEA
Wilder coal		BASAL COAL AND UNCONFORMITY	(1) MAXIMUM DROP	SWAMPS AND EROSION
SIGNAL POINT SH.		BLANKET SHALE	(4) MAXIMUM RISE	DEEP SEA
Lower Wilder coal		COAL	(3) MODERATE DROP	SWAMPS
WARREN POINT SS		BLANKET SANDSTONE	(2) MODERATE RISE	SHALLOW SEA
Upper Bon Air coal		BASAL COAL AND UNCONFORMITY	(1) MAXIMUM DROP	SWAMPS AND EROSION

FIGURE 8.—CLASSIFICATION OF PART OF THE LOWER PENNSYLVANIAN OF TENNESSEE AS FIVE CYCLOTHEMS

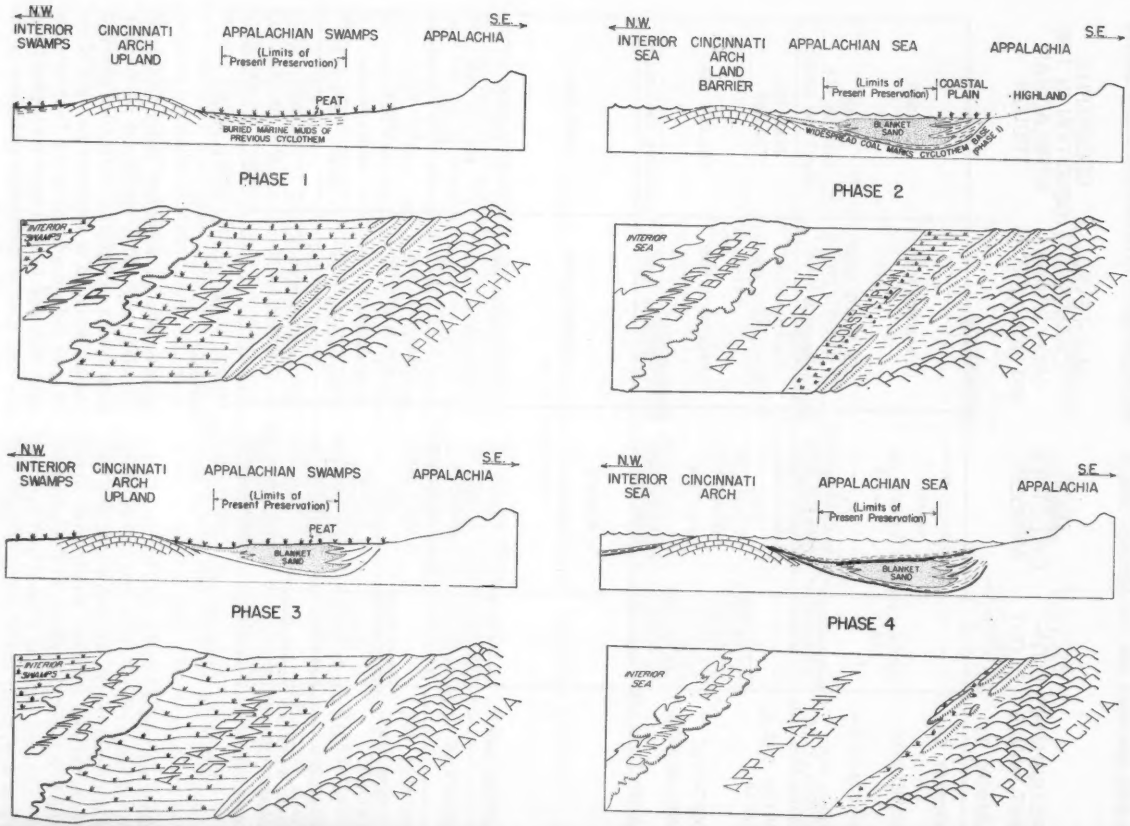

FIGURE 9.—GEOLOGY AND PHYSIOGRAPHY OF EASTERN TENNESSEE DURING THE PHASES OF A TYPICAL CYCLOTHEM

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the sea rose to its highest level, advancing far beyond the shore lines of the older shallow marine invasion. The entire Tennessee coal field was a deep-water area with a mud bottom. The Cincinnati arch was largely submerged, but perhaps it still remained as a narrow barrier between the Appalachian Sea and the Interior Sea. Bordering lowlands of Appalachia were also submerged.

A similar paleogeographic picture is visualized for each of the widespread shale deposits. However, progressive burial of the Cincinnati arch probably resulted in the complete submergence of this feature and the extension of the Interior Sea to the shore of Appalachia during later Pennsylvanian time. At the close of phase 4, the entire cycle ended abruptly as the sea again withdrew by a eustatic lowering of sea level (*See* Fig. 9).

Conclusions

The writers have presented a unified rational system of stratigraphy and paleogeography for some of the more extensive and better known Pennsylvanian strata in Tennessee. This is based on the known distribution and vertical and areal variations in character of sandstones, shales, and coal beds, together with a series of new fossil discoveries. These lithologic and paleontologic data are combined with the regional structure pattern and the concept of the four-phase eustatic sea-level cycle to derive a historical geologic "model," which is a combination of two causal factors—(1) regional eustatic variation in water depth, and (2) local intermittent interplay between structural subsidence of the Appalachian trough and rapid sedimentation adjacent to the source area (Appalachia). The first factor tends to result in widespread blankets of sediment (and cyclothems); the second results in abrupt local changes, particularly to the southeast nearest to Appalachia (and obscures cyclothems). From this geologic "model" the writers have offered an explanation for many stratigraphic relationships that heretofore were not readily explained and have rationalized the stratigraphy into a paleogeographic sequence in considerable detail.

Although the "model" explains Pennsylvanian stratigraphy genetically, the writers do not intent to maintain that it is the ultimate concept. It depends in large measure on the correctness of two conclusions—(1) that the bulk of Pennsylvanian strata is marine, and (2) that a four-phase cycle of eustatic sea-level changes controlled cyclothemic sedimentation. The first of these basic conclusions can be further investigated in Tennessee and adjacent areas of the southern Appalachian coal field by continued mapping, measuring sections, and searching for fossils. The applicability of the four-phase eustatic cycle needs testing on other continents; if it is true anywhere it must be true in all areas where such eustatic changes would have influenced depositional environments.

Even though a cyclothem concept can be applied as a genetic classification, the writers do not intend that it should supplant other systems as a practical basis for nomenclature of map units. Rather than as a rock-unit classification in this region of rapid lateral changes, it should presently be considered as a tool for comparative stratigraphy because of its possibilities for precise local, regional, and interregional time-rock correlation.

FIGURE 9.—GEOLOGY AND PHYSIOGRAPHY OF EASTERN TENNESSEE DURING THE PHASES OF A TYPICAL CYCLOTHEM

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PETROLOGY OF SEVERAL PEGMATITES IN THE KEYSTONE DISTRICT, BLACK HILLS, SOUTH DAKOTA

BY P. M. ORVILLE

ABSTRACT

Three pegmatites in the vicinity of Keystone, South Dakota, of simple mineralogy and without concentric zoning have been studied in detail. They occur within Precambrian quartz-mica schist and are peripheral to the Precambrian Harney Peak granite. Two are concordant to schistosity and bedding of the country rock, and the third is sharply discordant. These pegmatites are of very similar average modal and chemical compositions. Samples of the Harney Peak granite from two localities have compositions close to those of the pegmatites. All the compositions fall near the quartz-feldspar field boundary in the "synthetic-granite" system. The average composition of pegmatites and granite is approximately 30 per cent quartz, 44 per cent plagioclase, 17 per cent microcline, 8 per cent muscovite, and less than 1 per cent tourmaline, garnet, and apatite.

Large perthite crystals appear to have grown, at least in part, by pushing aside previously crystallized fine-grained quartz and plagioclase. This relationship is compatible with experimental findings which indicate that in a melt of this composition, crystallization, whether of the one- or two-feldspar types, should begin with quartz and a Na-rich feldspar.

At one locality thin, steeply dipping tabular pegmatites are sharply separated into an upper porphyritic perthite-bearing unit and a lower fine-grained albite-quartz unit. The upper, perthite-bearing unit of the layered pegmatites has a composition near that of the "granite minimum" in the "synthetic-granite" system and is thought to represent a rest liquid which has been separated from the phases which crystallized earlier.

The pegmatites and granite are believed to have been intruded as magma derived from a common source.

CONTENTS

TEXT

	Page
Introduction	1468
Acknowledgments	1468
Field relationships	1469
Description of rock bodies	1470
Grain-size terminology	1470
Camp Judson pegmatite	1470
Burnt Area pegmatite	1472
Buell Ranch pegmatite complex	1474
Harney Peak granite	1476
Characteristics of individual minerals	1477
Composition of rock bodies	1479
Sampling and determinative methods	1479
Camp Judson pegmatite	1479
Burnt Area pegmatite	1481
Buell Ranch pegmatite complex	1481
Harney Peak granite	1482
Discussion	1484
References cited	1489

ILLUSTRATIONS

Figure	Page
1. Index map of southern Black Hills and Keystone district, South Dakota, showing sample localities and access roads	1469
2. Typical relationships between perthite megacrysts and tourmaline-bearing laminations	1471
3. "Breccia" structure, Camp Judson pegmatite	1472
4. Geologic map of Buell Ranch pegmatite complex	1473
5. Typical sequence of units in layered members, Buell Ranch pegmatite complex	1474
6. Layering in portion of Buell Ranch pegmatite complex	1475
7. Stereographic equal-area plot of orientations of muscovite grains in a quartz-muscovite intergrowth	1476
8. Quartz-perthite fracture filling, Buell Ranch pegmatite complex	1476
9. Modal compositions of granite and pegmatites plotted on liquidus of synthetic-granite system	1486
10. Modal compositions of units within Buell Ranch pegmatite complex plotted on liquidus of synthetic-granite system	1488
11. Porphyritic unit which cuts across series of tourmaline-bearing laminations	1488

Plate	Facing page
1. Outcrops of Camp Judson pegmatite and layered pegmatite of Buell Ranch pegmatite complex	1472

Plate — Facing page
2. Thin sections of rocks from the Keystone district, Black Hills, South Dakota 1473

TABLES

Table — Page
1. Chemical and modal compositions of quartz-muscovite schist, Keystone district, South Dakota 1470
2. Pegmatite grain-size terminology 1471
3. Modal and chemical compositions of perthite megacrysts, Keystone district, South Dakota 1477
4. Chemical and modal compositions of Camp Judson pegmatite 1478
5. Rosiwal analysis of outcrop, Burnt Area pegmatite 1479
6. Chemical and modal compositions of Burnt Area pegmatite 1480
7. Modal composition of fine-grained units, Buell Ranch pegmatite complex 1481
8. Statistical analysis of modal analyses of fine-grained units 1482
9. Chemical and modal compositions of Buell Ranch pegmatite complex 1483
10. Chemical and modal compositions of Harney Peak granite 1484
11. Chemical and modal compositions of pegmatites and granite, Keystone district, South Dakota 1585

Introduction

The principal aim of this investigation has been to determine the chemical and mineralogical compositions of several unzoned and layered pegmatites in the Keystone district, which is at the northeast edge of the large mass of granitic rocks surrounding Harney Peak in the southern Black Hills, South Dakota (Fig. 1). Compositions of the granite have also been determined at two localities within the main granite mass.

A comparison of the compositions of the pegmatites with one another and with the granite will help to account for the origin of both the pegmatites and granite. Knowledge of the natural rock compositions permits the petrographic interpretation of textures and structures within the pegmatites to be supplemented by laboratory data from the "synthetic-granite" and "ternary-feldspar" systems.

The irregular textures and structures and large average grain size within pegmatite bodies have made conventional petrographic studies difficult. Many early investigations of pegmatites were entirely mineralogical. Individual minerals, commonly rare or unusual, were studied, and the main mass of pegmatitic material was largely ignored. In recent years there have been many comprehensive descriptive studies of concentrically zoned pegmatites. In most cases, however, quantitative data on the bulk composition have not been obtained. Notable exceptions are the studies of Jahns (1953) and Sheridan *et al.* (1957).

Pegmatite investigations have dealt mainly with commercially important bodies which contain minable concentrations of feldspar, lithium minerals, beryl, or muscovite. Almost without exception these are concentrically zoned, and they constitute only a very small proportion of the total pegmatite population within a given district. Pegmatites which are not concentrically zoned have been ignored for the most part despite the fact that in terms of number and mass of material they make up the greatest part of most pegmatite districts. Detailed studies of such pegmatites have been made by Staatz and Trites (1955) in the Quartz Creek area, Colorado, and by J. A. Redden (1955, Ph.D. thesis, Harvard Univ.) in the Four Mile area, South Dakota.

Three pegmatites in the vicinity of Keystone, South Dakota, have been analyzed in detail. The Camp Judson pegmatite has essentially the same texture and composition throughout and is of the type described as unzoned by Cameron *et al.* (1949). The Burnt Area pegmatite, of tabular form, is separated into two units of differing composition by a plane approximately parallel to the median plane of the body and therefore can be classified as a layered pegmatite, as defined by Staatz and Trites (1955). The Buell Ranch pegmatite complex consists of a large number of closely associated tabular pegmatite bodies and includes both unzoned and layered types. Figure 1 shows the locations of these pegmatites and the two sample localities within the Harney Peak granite.

Acknowledgments

This paper represents part of a dissertation submitted to Yale University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. This investigation has received financial support from Yale University, The Geological Society of America, and the Carnegie Institution of Washington. I am grateful to the U. S. Geological Survey for two chemical analyses performed by the Rapid Rock Analysis Laboratory and for permission to publish two analyses performed for J. J. Norton.

Profs. Matt Walton and R. H. Jahns, Dr.

Felix Chayes, and Dr. Sydney P. Clark have read all or a part of this manuscript, and I am grateful to them for their many helpful comments and suggestions.

The quartz-mica schist, the dominant country rock, contains quartz as the major mineral; subordinate amounts of oligoclase (An_{18-30}), biotite, and muscovite; and minor amounts of

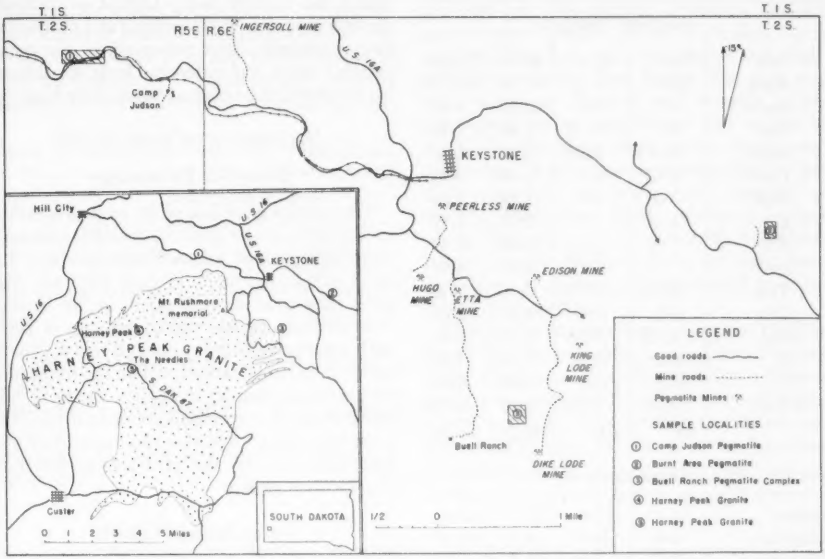

FIGURE 1.—INDEX MAP OF SOUTHERN BLACK HILLS AND KEYSTONE DISTRICT, SOUTH DAKOTA, SHOWING SAMPLE LOCALITIES AND ACCESS ROADS

Contact of Harney Peak granite is from Darton and Paige (1925) as modified by J. A. Redden (unpub. manuscript, U. S. Geological Survey).

FIELD RELATIONSHIPS

The pegmatites in the southern Black Hills lie in a metamorphic terrain of micaceous schist, quartzite, and amphibolite surrounding the Harney Peak granite. The granite is roughly circular in outcrop plan, with a diameter of approximately 9 miles. Much of it has a porphyritic texture similar to unzoned pegmatites in the area. In the peripheral regions of the granite, large tabular bodies of granitic rock are interspersed with layers of schistose country rock. Farther away from the main granite mass the proportion of schist increases, and schist encloses discrete bodies of pegmatite.

Rubidium-strontium age determinations of muscovite from pegmatites in the Keystone district give ages of 1700 million years for the Bob Ingersoll pegmatite, a zoned pegmatite, and 1760 million years for the Buell Ranch pegmatite complex (G. L. Davis and G. R. Tilton, personal communication).

microcline, graphite, and tourmaline. The average grain size is about 0.2 mm. The schist is quite uniform in composition at the Buell Ranch and Burnt Area localities, but at the Camp Judson locality quartz-rich and mica-rich rocks are interlayered in beds several inches to several feet thick. Bedding is parallel to schistosity wherever it can be observed. Table 1 gives chemical and modal analyses of schist samples.

The contacts between pegmatite and country rock are very sharp, and the schist in most places shows only slight or no contact effects. No consistent differences in texture or composition have been found between schist within a few inches of a pegmatite contact and schist hundreds of feet away. Graphite and tourmaline are locally enriched in schist where late quartz-rich fracture fillings cut across the pegmatite and terminate at the schist contact. The pegmatite contacts at the Buell Ranch and Burnt Area localities are, in general, conformable to the schistosity and bedding of the country rock,

TABLE 1.—CHEMICAL AND MODAL COMPOSITIONS OF QUARTZ-MUSCOVITE SCHIST, KEYSTONE DISTRICT, SOUTH DAKOTA

	46–56	47–56	48–56	49–56
Chemical Analyses				
SiO_2	66.6	82.6	80.99	79.48
Al_2O_3	16.0	9.8	9.59	10.36
Fe_2O_3	1.5	0.7	0.82	0.62
FeO	4.1	0.82	1.91	2.19
MgO	2.1	0.52	0.80	0.84
CaO	0.47	1.1	0.50	0.63
Na_2O	1.2	3.0	1.50	1.88
K_2O	5.4	1.1	2.07	2.12
H_2O^-	1.5	0.37	0.05	0.04
H_2O^+			0.94	0.97
TiO_2	0.59	0.28	0.39	0.43
CO_2	n.d.	n.d.	0.01	0.01
P_2O_5	0.13	0.04	0.12	0.15
Cl	n.d.	n.d.	0.01	0.01
F	n.d.	n.d.	0.04	0.04
MnO	0.06	0.06	0.02	0.03
	100	100	99.76	99.80
Modal Analyses				
Quartz	26.2	55.6	57.7	68.6
Oligoclase	6.4	30.4	19.8	12.3
Microcline	10.1	3.8	0.5	..
Biotite	20.8	2.2	4.7	8.8
Muscovite	35.4	7.6	8.2	10.0
Graphite	0.3	0.5	1.6	0.2
Tourmaline	0.7	..	..	..
Apatite	0.2	..	0.1	0.2
Fibrous alt.	..	..	0.4	..
Area of sample (mm^2)	1000	1000	4000	1000

46–56. Chemical analysis by Rapid Rock Analysis Laboratory, U. S. Geological Survey, Washington, D. C. From mica-rich bed; collected 800 feet northeast of Camp Judson pegmatite (Fig. 1). Schistose texture with average grain size 0.1–0.2 mm. Microcline forms small augen around which mica flakes are bent. Plagioclase (An_{15}) is fresh and untwinned.

47–56. Chemical analysis by Rapid Rock Analysis Laboratory, U. S. Geological Survey, Washington, D. C. From quartz-rich bed; collected 800 feet northeast of Camp Judson pegmatite (Fig. 1). Granulose texture with average grain size 0.1–0.2 mm. Plagioclase (An_{17}) is fresh and untwinned.

48–56. Chemical analysis by Lucile N. Tarrant, U. S. Geological Survey. Analyses performed for J. J. Norton, U. S. Geological Survey. Composite sample collected 300 feet east of Buell Ranch pegmatite complex (Fig. 1). Seriate granulose texture with average grain size 0.2 mm. Plagioclase (An_{30}) is sparsely twinned and commonly contains graphite inclusions.

49–56. Chemical analysis by Lucile N. Tarrant, U. S. Geological Survey. Analysis performed for J. J. Norton, U. S. Geological Survey. Sample collected from 20-foot wide schist parting within Buell Ranch pegmatite complex. Texture schistose with average grain size 0.2 mm. Plagioclase (An_{17}) sparsely twinned.

although they may be locally discordant. The contacts of the Camp Judson pegmatite transect the bedding and schistosity at a large angle. Minerals which occur as large crystals within the pegmatites do not occur as porphyroblasts within the country rock. Original sedimentary structures such as cross-bedding and channeling have commonly been preserved in the metamorphic rocks, and individual beds of contrasting composition have maintained their identity.

DESCRIPTION OF ROCK BODIES

Grain-Size Terminology

The average grain size of the rocks is specified by the terms meter-grained, decimeter-grained, centimeter-grained, and millimeter-grained. Table 2 defines the limits of each term and also gives their near equivalents in inches or feet. This terminology has the advantages of being both descriptive of grain size and free of genetic and textural implications, unlike the terms pegmatite (or pegmatitic) and aplite. Terms such as fine-grained or very coarse-grained are useful in a specific context, and there seems no reason to force them to carry the burden of an arbitrary classification system.

Camp Judson Pegmatite

The Camp Judson pegmatite is in the NE ¼ sec. 2 and NW ½ sec. 1, T.2 S., R.6 E. It is 3.0 miles west northwest of Keystone, South Dakota, and 0.7 mile west-northwest of Camp Judson, a Baptist church camp. The pegmatite crops out as an almost vertical wall (Pl. 1, fig. 1) along the north side of an improved dirt road following the valley of Battle Creek, and its highest point is 200 feet above the valley floor.

The pegmatite is a nearly vertically dipping dike which is sharply discordant to the schistosity and bedding of the country rock. Its length is at least 2000 feet. Its width ranges from 8 to

120 feet but for most of its extent is about 80 feet. It strikes approximately N. 80°E., and the average dip of both contacts is 80° to the south. Schistosity and bedding of the country rock strike N.80° E. and dip 30°–45° north.

Except for minor border facies, the pegmatite consists of a single compositional and textural unit, porphyritic albite-quartz-perthite rock. Subhedral to anhedral graphic granite megacrysts, of 2 to 24 inches, make up approximately 20 per cent of the rock; the groundmass consists of millimeter-grained albite-quartz rock (Pl. 2, fig. 2) which is distinctly laminated in alternating dark and light layers 5 to 20 mm in width. This contrast in color is due to 5 to 10 per cent very fine-grained tourmaline and approximately 1 per cent garnet in the dark layers and less than 2 per cent tourmaline and negligible garnet in the light layers. The dark and light layers are identical with respect to the other groundmass constituents and consist of approximately 34 per cent quartz, 54 per cent plagioclase (An_6), 4 per cent microcline, 4 per cent muscovite, and a very small amount of apatite. Plagioclase forms subhedral equant grains of approximately 2 mm in which are embedded smaller rounded quartz grains. Microcline forms irregular grains interstitial to or included in plagioclase.

TABLE 2.—PEGMATITE GRAIN-SIZE TERMINOLOGY

	Average Grain Sizes	
	(Meters)	(Approx. Equivalents)
Meter-grained	0.32–3.2	1–10 feet
Decimeter-grained	0.032–0.32	1–12 inches
Centimeter-grained	0.0032–0.032	0.1–1.0 inches
Millimeter-grained	0.00032–0.0032	0.01–0.1 inches

The tourmaline-rich laminations are roughly parallel to the pegmatite borders, but in detail their orientation is influenced by adjacent perthite megacrysts. The relationships of megacrysts to laminations in the groundmass are quite variable (Fig. 2). The types of distortion shown in Figure 2, where carried to an extreme, produce a breccialike texture in which separate

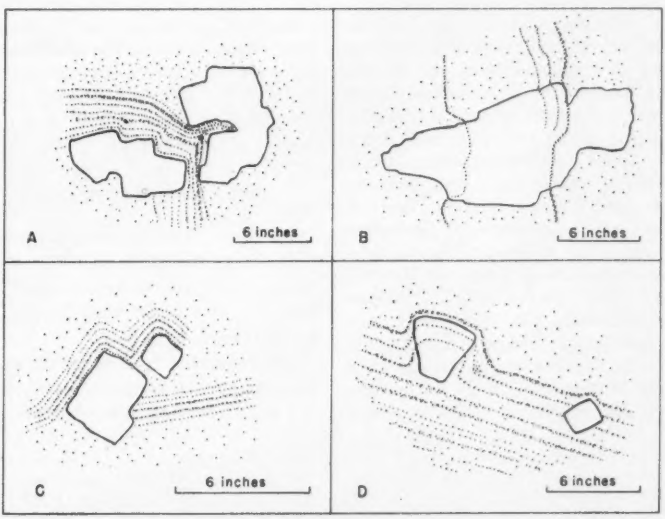

FIGURE 2.—TYPICAL RELATIONSHIPS BETWEEN PERTHITE MEGACRYSTS AND TOURMALINE-BEARING LAMINATIONS

A, laminations crowded between megacrysts. B, laminations included within megacrysts as "phantoms" with slight or no distortion. C, laminations truncated and displaced by megacrysts. D, distorted laminations included within megacrysts as phantoms. Based on photographs or sketches made in field.

patches of contorted and apparently displaced laminated rock are crowded between large perthite crystals (Fig. 3). Some perthite megacrysts contain dark tourmaline-bearing layers which are continuous with tourmaline-rich laminations in the fine-grained groundmass. A layer may pass through a perthite megacryst without deflection but more commonly is bent.

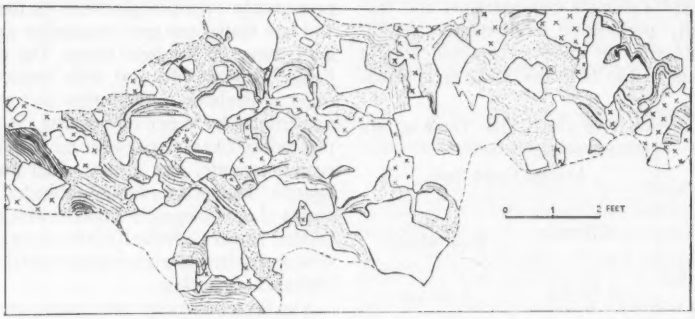

FIGURE 3.—"BRECCIA" STRUCTURE, CAMP JUDSON PEGMATITE

Outcrop surface is nearly vertical, and in general it makes a rather small angle with attitude of laminations. Patches of fine-grained laminated rock are interstitial to large perthite crystals (blank) and coarse-grained quartz-muscovite-perthite rock (X pattern).

Nearly all megacrysts contain plagioclase and quartz inclusions. Quartz occurs both as graphic grains in optical continuity with one another and as irregular grains with diverse orientations. Most of the plagioclase occurs as regularly oriented lamellae in parallel crystallographic orientation with their host, but some is in diversely oriented subhedral grains (Pl. 2, fig. 1). Irregular quartz grains and diversely oriented plagioclase grains tend to occur together in clots, and they are especially abundant in the outer portions of megacrysts and associated with tourmaline in "phantom" laminations. These island clots within the perthite megacrysts have essentially the same texture as the fine-grained plagioclase-quartz groundmass, and some apparent inclusions appear to be physically continuous with the fine-grained groundmass. The plagioclase which occurs in regular lamellae is presumably of exsolution origin, but the plagioclase which occurs in irregular grains, both by itself and with quartz, appears to be genetically related to both the tourmaline-bearing layers within the perthite megacrysts and to the fine-grained groundmass outside.

The pegmatite is commonly nonporphyritic up to 2 feet from the contact of the dike. Its texture is similar to that of the laminated groundmass of the porphyritic rock but differs in that some layers are rich in microcline. Where perthite megacrysts are present in this marginal zone they are much smaller than in the main portion of the pegmatite.

Burnt Area Pegmatite

The Burnt Area pegmatite is in the NW ¼ of the SE ¼ sec. 11, T.2 S, R.6 E. It is approximately 3 miles east of Keystone and is 1000 feet northeast of a gravel road between Keystone and Hayward.

The pegmatite is a steeply dipping tabular body which extends approximately 750 feet and is 2 to 25 feet wide. The borders of the pegma-

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PLATE 1.—OUTCROPS OF CAMP JUDSON PEGMATITE AND LAYERED PEGMATITE OF BUELL RANCH PEGMATITE COMPLEX

FIGURE 1.—Camp Judson pegmatite. Contacts are nearly vertical. Schistosity and bedding of schist are gently dipping. Lineation on pegmatite wall is parallel to intersection of pegmatite contact and schistosity. View is toward northeast.

FIGURE 2.—Layered pegmatite member, Buell Ranch pegmatite complex. Porphyritic unit at right.

FIGURE 1

FIGURE 2

OUTCROPS OF CAMP JUDSON PEGMATITE AND LAYERED PEGMATITE OF BUELL RANCH PEGMATITE COMPLEX

FIGURE 1

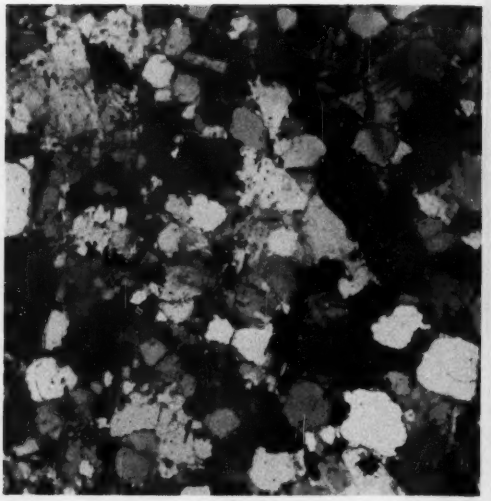

FIGURE 2

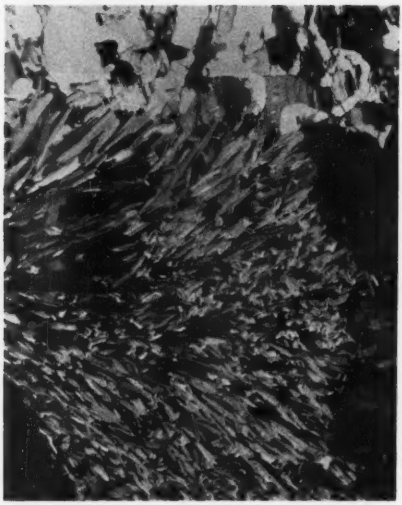

FIGURE 3

FIGURE 4

THIN SECTIONS OF ROCKS FROM THE KEYSTONE DISTRICT, BLACK HILLS, SOUTH DAKOTA

tite are generally conformable with the schistosity and bedding of the country rock. This pegmatite is predominantly porphyritic, consisting of subhedral graphic granite megacrysts of vite groundmass. The hanging-wall portion contains a significantly higher proportion of graphic granite megacrysts and quartz-muscovite pods than the footwall portion. The mega-

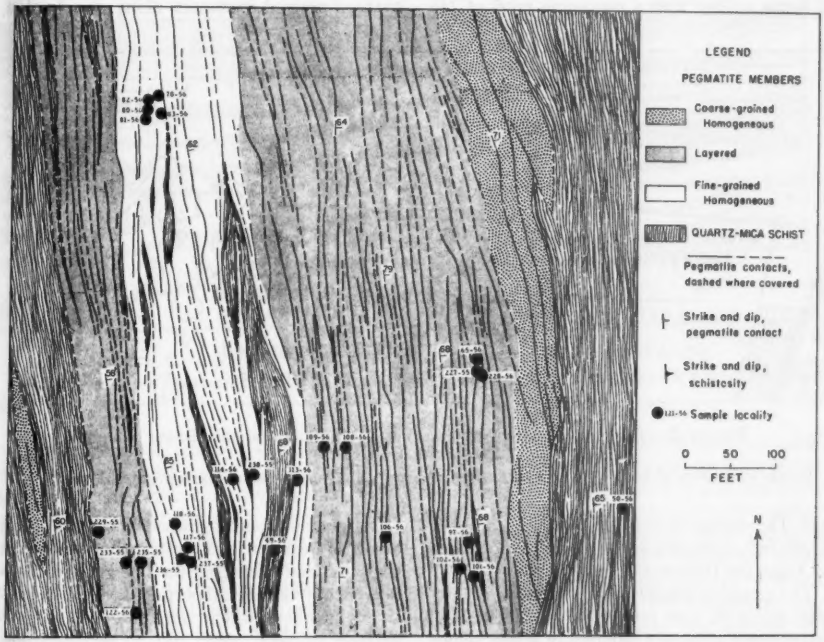

FIGURE 4.—GEOLOGIC MAP OF BUELL RANCH PEGMATITE COMPLEX

about 1 foot which tend to be elongate in the a crystallographic direction of microcline and a small number of quartz-muscovite pods embedded in a fine-grained albite-quartz-muscocrysts show a preferred orientation, with their long dimension approximately normal to the pegmatite contacts. A few tourmaline-rich laminations are present in the footwall unit.

PLATE 2.—THIN SECTIONS OF ROCKS FROM THE KEYSTONE DISTRICT, BLACK HILLS, SOUTH DAKOTA

FIGURE 1.—Microcline perthite megacryst. Note irregular plagioclase lamellae, subhedral plagioclase inclusion and graphically intergrown quartz (quartz, white; microcline, dark; plagioclase, gray). Magnification 10×, polarized light with crossed nicols.

FIGURE 2.—Fine-grained groundmass, Camp Judson pegmatite. Quartz occurs as equant, rounded grains included within somewhat larger anhedral plagioclase grains. Very small tourmaline prisms concentrated in lamination on left side. Magnification 25×, polarized light with crossed nicols.

FIGURE 3.—Quartz-muscovite intergrowth with simple fanlike cross section. Contact with perthite megacryst to right and fine-grained albite-quartz groundmass above. Magnification 8×, polarized light with crossed nicols.

FIGURE 4.—Elongate, plumose, quartz-muscovite intergrowths. Quartz, dark; muscovite, light. Magnification 10×, polarized light with crossed nicols.

Buell Ranch Pegmatite Complex

The Buell Ranch pegmatite complex (Fig. 4) is approximately 2 miles south of Keystone in the NW ¼ of the NE ¼ sec. 21, T.2 S., R.6 E. It forms a ridge with a maximum relief of 240 feet. The contact of the Harney Peak granite is shown half a mile southwest of the mapped area by Paige (*in* Darton and Paige, 1925).

The complex consists of thin sheets of granitic material, here referred to as "members," interlayered with thin partings of schist, which have a combined thickness of about 800 feet. Within the map area, granitic material predominates, but 1000 feet to the north the proportion of country rock is larger, and the pegmatite forms irregular podlike bodies surrounded by schist. The pegmatites and schist strike approximately north-south and dip steeply to the east. The partings range from a fraction of an inch to more than 20 feet in width; most are several inches wide. In places they are missing and only a planar "knife edge" discontinuity separates adjacent pegmatite members. The tabular pegmatite members are concordant or very nearly so. Several of the partings may be traced continuously for at least 300 feet, and a number are inferred to be 500 feet or more long. They have been observed to pinch out in both horizontal and vertical directions. In some cases the parting continues as a planar discontinuity, and in others adjacent pegmatites coalesce to form a single member.

The pegmatites range in thickness from less than 1 foot to 20 feet, and most are about 6 feet thick. Many are divided into two or more textural and compositional units. A gross zoning is apparent within the complex as a whole (Fig. 4). Generally speaking, the finest-grained members occur in the center of the complex, and the coarsest-grained members along the borders.

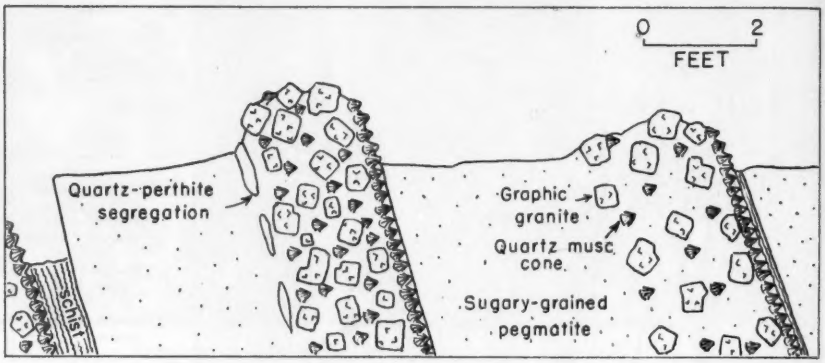

FIGURE 5.—TYPICAL SEQUENCE OF UNITS IN LAYERED MEMBERS, BUELL RANCH PEGMATITE COMPLEX

Porphyritic units at hanging wall and fine-grained units at footwall within each pegmatite member.

Homogeneous coarse-grained members occur along the eastern and western borders of the complex, and homogeneous fine-grained members occupy the central portion. Layered pegmatites, members which are split into a fine-grained footwall unit and a coarse-grained hanging-wall unit, occur between these members. Individual layered members may grade into either type of homogeneous member along their strike.

HOMOGENEOUS MEMBERS: Homogeneous coarse-grained members are decimeter-grained rock with a porphyritic texture. The rock consists of blocky graphic granite crystals of about 6 inches in a matrix of albite (An_6), quartz, and muscovite in grains of three-quarters of an inch. The approximate mode of these members, based on visual estimates, is: albite, 40 per cent; quartz, 30 per cent; microcline, 20 per cent; muscovite, 10 per cent; tourmaline, less than 1 per cent.

Homogeneous fine-grained members are millimeter-grained rock with a seriate granoblastic texture. Quartz and plagioclase are in equant anhedral grains; microcline forms irregular interstitial grains and patchy inclusions within plagioclase and muscovite, and biotites are in subhedral plates. Tourmaline, apatite, and garnet occur as sparse subhedral to euhedral grains.

Average modal composition from Table 7 is: quartz, 33 per cent; albite (An_{3-7}), 41 per cent; microcline, 13 per cent; muscovite, 12 per cent; biotite, tourmaline, apatite, and garnet, less than 1 per cent each.

The graphic granite megacrysts are subhedral, equant microcline-perthite crystals of about 6 inches, containing 15 to 25 per cent graphically intergrown quartz and 15 to 20 per cent plagioclase.

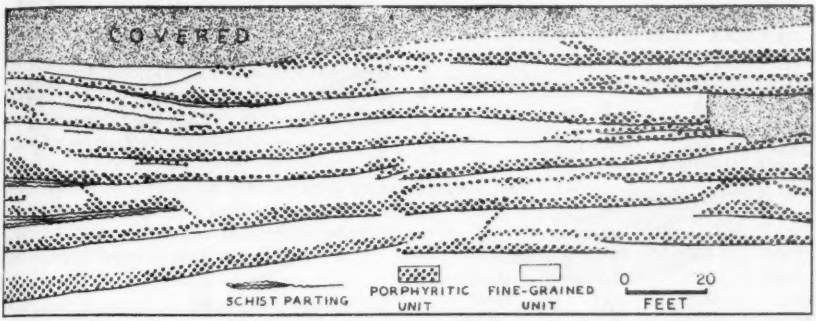

FIGURE 6.—LAYERING IN PORTION OF BUELL RANCH PEGMATITE COMPLEX
Pegmatite contacts dip approximately 65° toward bottom of figure. Area represented is near southeast corner of Figure 4.

LAYERED MEMBERS: Figure 5 and Figure 2 of Plate 1 show a typical sequence of units within the layered members. Each member is most commonly split into two units, a lower perthite-poor fine-grained unit, and an upper perthite-rich porphyritic unit. The fine-grained unit is commonly 1.5 times as thick as the porphyritic unit. The boundary between the two units is commonly marked by thin lenses of quartz-perthite pegmatite. The intimate relationships between the layering and the pair of parting discontinuities which define each member are clearly shown in Figure 6. Some layered members, particularly in the western portion of the complex, contain more than a single pair of porphyritic and fine-grained units.

The porphyritic units are made up of 10 to 55 per cent (most commonly about 40 per cent) graphic granite megacrysts and 5 to 25 per cent cone-shaped quartz-muscovite intergrowths embedded in a millimeter-grained albite-quartz-biotite groundmass. Generally units which are rich in graphic granite megacrysts are also rich in quartz-muscovite intergrowths. The megacrysts are uniformly distributed and diversely oriented within the units. The quartz-muscovite intergrowths are scattered throughout the porphyritic unit, but immediately adjacent the hanging-wall partings they form an almost solid layer. Almost without exception, the axis of the cone is perpendicular to the walls, and the apex of the cone points toward the hanging wall.

The quartz-muscovite cones have an apical angle of approximately 60° and an axial length of half an inch to 6 inches, 2 to 3 inches being the average. The smaller cones are more regular in form and generally consist of a radiating intergrowth of lath-shaped muscovite grains within a groundmass consisting of a single quartz grain (Pl. 2, fig. 3). The larger cones consist of a number of elongate quartz-muscovite intergrowths in more or less parallel alignment (Pl. 2, fig. 4). The proportions of quartz and muscovite in the intergrowths are approximately equal. Gates (1954) and Jahns and Wright (1951, p. 19) have described similar muscovite aggregates in pegmatites.

Study of the quartz-muscovite intergrowths on the Universal stage shows that the c crystallographic axis of the quartz is parallel to the axis of the cone and that the direction of elongation of the muscovite blades corresponds to the b crystallographic axis of the muscovite. Figure 7 shows these relationships.

The lower fine-grained units are millimeter-grained rock with a seriate granoblastic texture. The units near the eastern and western contacts of the complex are coarser than those closer to the center. Table 7 gives modal analyses. The average unit contains: quartz, 35 per cent; albite (An_7), 51 per cent; microcline, 3 per cent; muscovite, 10 per cent; and biotite, tourmaline, apatite, and garnet, less than 1 per cent. Microcline occurs predominantly as small patchy

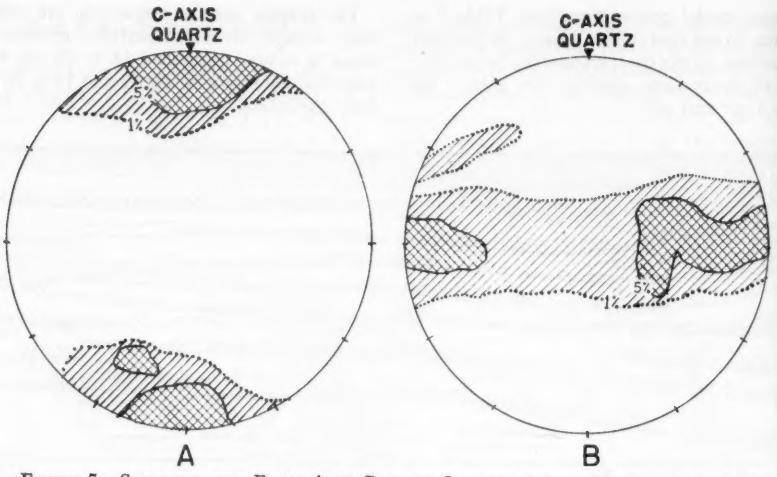

FIGURE 7.—STEREOGRAPHIC EQUAL-AREA PLOT OF ORIENTATIONS OF MUSCOVITE GRAINS IN A QUARTZ-MUSCOVITE INTERGROWTH

A, b axes (direction of elongation of muscovite lathes). B, poles to (001) cleavage of muscovite lathes. Approximately 150 grains; 1 and 5 per cent contours.

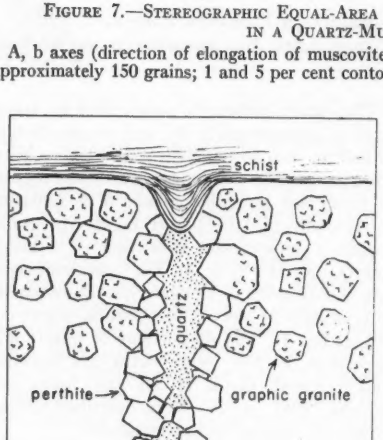

FIGURE 8.—QUARTZ-PERTHITE FRACTURE FILLING, BUELL RANCH PEGMATITE COMPLEX

Plan view of outcrop. Pegmatite contacts dip 65° toward top of page. Fracture filling consists of subhedral to euhedral perthite crystals free of graphic quartz. Several large graphic granite crystals grade into quartz-free perthite adjacent to the fracture filling.

grains included in, and in parallel crystallographic orientation with, plagioclase grains.

FRACTURE FILLINGS: Within the mapped area of the Buell Ranch pegmatite complex there are twelve fracture fillings. They are characterized by a tabular form, a crosscutting relationship to other pegmatite units in the complex, and a medium- to coarse-grained pegmatitic texture. They are rich in quartz and perthite and poor in plagioclase. Several consist only of quartz. Perthite is in subhedral to euhedral blocky crystals and is free of graphically intergrown quartz.

Most commonly each fracture filling cuts across a single pegmatite member, normal to its walls. Schist at both upper and lower contacts extends partway into the fracture as a "roll" (Fig. 8).

Harney Peak Granite

The Harney Peak granite is texturally and structurally diverse, with large- and small-scale mineralogical and textural layering, abundant inclusions of country rock, and crosscutting granitic bodies which are clearly later than the main mass. Much of the granitic rock near Sylvan Lake shows a crude, nearly horizontal layering. Irregular porphyritic layers rich in graphic granite megacrysts alternate with fine-grained layers on a scale of several feet. Small-scale laminations a few inches thick are also common. Coarser-grained layers, commonly rich in perthite, alternate with finer-grained

layers, which are comparatively rich in albite, muscovite, tourmaline, and garnet. The small-scale layering is strictly parallel to the contacts of inclusions of country rock and may or may not be conformable with the schistosity of the inclusions.

At the summit of Harney Peak and at many other locations the granite has a porphyritic texture which is identical with that of many of the homogeneous pegmatites in the area. Graphic granite megacrysts a foot or so in size are irregularly distributed in a fine-grained groundmass poor in microcline.

Bodies of fine-grained, even-textured granitic rocks also occur within the Harney Peak granite. These may be either separate intrusions or different facies of the more common porphyritic and layered types of granite.

Characteristics of Individual Minerals

QUARTZ: Quartz in the quartz-mica schist is generally unstrained; that in pegmatites or granite commonly shows moderate strain.

PLAGIOCLASE: Plagioclase in the quartz-mica schist is untwinned or rarely twinned, generally unaltered, and has a composition of An_{15-20}. In the pegmatites and granite it is abundantly twinned and commonly shows slight sericitic alteration and antiperthitic patches of microcline in the central portions of large crystals.

Although the Ca contents of the various rock bodies studied are similar, the plagioclase compositions range from An_{10} in the Harney Peak granite to An_{0-1} at the Burnt Area pegmatite. The high content of P_2O_5 and modal apatite in that pegmatite indicates that most of the Ca is in apatite.

MICROCLINE: Alkali feldspar in both schist and pegmatites shows grid twinning. X-ray examination of a number of microcline perthite megacrysts showed all to be "maximum microcline" (*See* Goldsmith and Laves, 1954). Microcline crystals larger than about 5 mm are perthitic and contain plagioclase lamellae 0.05 to 0.7 mm wide and up to 5 mm long. Most perthite megacrysts contain several per cent of plagioclase in irregular, diversely oriented grains in addition to the lamellae. They also commonly contain inclusions of quartz, either as irregular grains or as regular graphic intergrowths. The outer portions of perthite megacrysts commonly contain such large amounts of poikilitically included quartz and plagioclase that by eye they can be distinguished from the fine-grained groundmass only by the microcline cleavage.

The perthite megacrysts are blocky subhedral crystals which commonly are elongate parallel to the a crystallographic direction. In the Burnt Area pegmatite the megacrysts tend to be oriented with their long dimension normal to the

TABLE 3.—MODAL AND CHEMICAL COMPOSITIONS OF PERTHITE MEGACRYSTS, KEYSTONE DISTRICT, SOUTH DAKOTA

	A Camp Judson Pegmatite	B Burnt Area Pegmatite	C Harney Peak Granite
*Chemical Composition**			
SiO_2	70.40	68.6	69.7
Al_2O_3	15.7	17.1	16.7
Na_2O	2.20	2.66	2.69
K_2O	11.04	11.69	11.27
Modal Composition†			
Quartz	13.1	5.0	9.4
Albite	13.9	18.3	22.2
Microcline	72.5	76.4	66.2
Muscovite	0.3	0.1	0.8
Tourmaline	0.2	..	..
Area (mm^2)	8000	12000	4000

* Na_2O and K_2O determined for each sample by flame-photometer methods. Al_2O_3 and SiO_2 calculated on basis of the assumption that megacrysts consist entirely of alkali feldspar and quartz.

† Modal analyses performed on stained thin sections by point counting. Area of 1000 mm^2 equivalent to approximately 1500 points.

A. Average chemical and modal compositions of seven samples of perthite megacrysts from eastern end of Camp Judson pegmatite. Blocky microcline perthite crystals 4–12 inches in size which contain plagioclase lamellae (An_{0-1}) and graphically intergrown quartz.

B. Average chemical and modal compositions of seven samples of perthite megacrysts from the Burnt Area pegmatite. Subhedral microcline crystals approximately 12 inches in size which contain plagioclase lamellae (An_{0-1}) and sparse graphically intergrown quartz.

C. Average chemical and modal compositions of two samples of perthite megacrysts from porphyritic granite at the Harney Peak locality. Samples collected 100 feet northwest of fire tower on summit of Harney Peak. Blocky microcline perthite crystals 2–8 inches in size which contain plagioclase lamellae, graphically intergrown quartz and very sparse muscovite grains.

walls of the dike, but at the other localities no preferred orientation is evident.

Comparison of modal and chemical compositions of perthite megacrysts (Table 3) indicates that the amount of Na feldspar in submicroscopic intergrowth or solid solution in the microcline matrix is small. The average difference between total plagioclase and modal plagioclase

TABLE 4.—CHEMICAL AND MODAL COMPOSITIONS OF CAMP JUDSON PEGMATITE

	A Fine-Grained Groundmass		B Average Fine-Grained Groundmass	C Average Megacryst	D Total Composition Pegmatite
	72-55	76-55			
Chemical Composition (Weight Per Cent)					
SiO_2	74.72	75.50	75.11	70.40	73.9
Al_2O_3	15.46	14.88	15.17	15.71	15.7
Fe_2O_3	1.12	0.37	0.75	..	0.58
FeO	0.68	0.68	0.68	..	0.52
MgO	0.07	0.09	0.08	..	0.06
CaO	0.68	0.94	0.81	..	0.63
Na_2O	5.48	5.02	5.25	2.20	4.55
K_2O	1.09	1.67	1.38	11.04	3.63
H_2O^+	0.43	0.49	0.46	..	0.35
H_2O^-	0.10	nil	..	..	..
TiO_2	tr.	tr.	..	..	..
P_2O_5	0.19	0.24	0.22	..	0.17
MnO	0.03	0.02	0.02	..	0.02
LiO_2	0.04	0.04	0.04	..	0.03
	99.75	99.94			
Modal Composition (Volume Per Cent)					
Quartz	34.9	38.1	33.8	13.1	29.0
Plagioclase	56.8	47.5	54.0	13.9	44.3
Microcline	0.5	0.8	4.2	72.5	20.1
Muscovite	2.3	10.7	3.6	0.3	2.9
Tourmaline	4.9	1.8	3.4	0.2	2.6
Garnet	0.1	0.1	0.3	..	0.2
Apatite	0.2	0.2	0.3	..	0.2

A. Chemical and modal analyses of fine-grained groundmass of Camp Judson pegmatite. Chemical analyses by W. H. Herdsman. Both samples collected at eastern end of pegmatite body approximately 200 feet northwest of intersection of road and tracks of C. B. & Q. Railroad. Sample 72-55 from area of outcrop which shows approximately 30 per cent graphic perthite megacrysts and 70 per cent fine-grained groundmass, and sample 76-55 from area of outcrop which shows approximately 15 per cent graphic perthite megacrysts and 85 per cent fine-grained groundmass. Seriate, granoblastic texture with average grain size about 1.5 mm. Prominent layering results from alternation of tourmaline-rich and tourmaline-poor laminations averaging 1 cm thick.

B. Chemical composition of fine-grained groundmass, average of chemical analyses of samples 72-55 and 76-55; modal composition, average mode of 10 specimens of fine-grained groundmass from eastern end of Camp Judson pegmatite. Total area 10,000 square mm and 15,300 points.

C. Average chemical and modal compositions of seven perthite specimens from Camp Judson pegmatite (Table 3).

D. Total chemical and modal composition of Camp Judson pegmatite calculated from columns B and C and outcrop modal analysis which shows 23.3 per cent megacrysts and 76.6 per cent groundmass over a traverse length of 309.1 feet.

is about 4 weight per cent. This amount of plagioclase, calculated as weight per cent of the microcline matrix, gives a composition of approximately $Or_{95}(Ab + An)_5$ for the optically homogeneous microcline.

MUSCOVITE: Muscovite occurs both in small subhedral dispersed plates and in coarse-grained intergrowths with quartz. Quartz-muscovite intergrowths with a well-developed cone structure are a prominent feature of the Buell Ranch pegmatite complex, and a few scattered quartz-muscovite cones occur within the Camp Judson pegmatite.

BIOTITE: Biotite is a major constituent of the country rock at all localities studied and is a minor constituent of the granite and pegmatite rocks except at the Burnt Area pegmatite. Biotite from the schist is fresh and pleochroic; it ranges from buff to orange-brown or red-brown. In the pegmatites and granite, the biotite is generally somewhat altered and is light brown to dark olive brown.

TOURMALINE: Tourmaline is an accessory mineral in all the pegmatites studied and in the granite, and it is present in very small amounts in much of the schist. In the pegmatites it forms stubby to elongate euhedral prisms with pleochroism ranging from buff to deep blue. In the Harney Peak granite it is generally in irregular intergrowth with quartz; its pleochroism ranges from buff to deep grayish green. Tourmaline in schist forms tiny euhedral equant grains with pleochroism ranging from buff to deep grayish green.

GARNET: Garnet in pink euhedra (1–5 mm) is a common accessory in all the pegmatites studied, and it is the principal accessory mineral in the Harney Peak granite.

APATITE: Apatite, a common accessory in the pegmatites, is present in most specimens of schist and is rare or absent in the Harney Peak granite. Within the pegmatite rocks it occurs as irregular equant grains up to several millimeters in size.

COMPOSITION OF ROCK BODIES

Sampling and Determinative Methods

The predominantly porphyritic texture of the pegmatites makes it very difficult to obtain a representative sample of the entire mass. Average compositions have been determined by sampling separately the fine-grained groundmass and the perthitic megacrysts and weighting the individual compositions according to the relative proportions of groundmass and megacrysts.

Compositions of aplitic rock and the groundmass of porphyritic rock have been determined both by chemical analysis of composite or representative samples and by modal analysis. The composition of the perthitic megacrysts has been determined by modal analysis and by partial chemical analysis. K_2O and Na_2O were determined by means of a Perkin-Elmer model 143 flame photometer.

TABLE 5.—ROSIWAL ANALYSIS OF OUTCROP, BURNT AREA PEGMATITE

	Perthite Megacrysts (Vol. Per Cent)	Quartz-Muscovite Intergrowths (Vol. Per Cent)	Fine-Grained Groundmass (Vol. Per Cent)	Total Traverse Length (Feet)	Width of Unit (Feet)
Hanging-wall unit	29	9	62	72.0	10
Footwall unit	14	3	83	77.0	10
Average	21.5	6	72.5		

The An content of plagioclase has also been determined from the minimum refractive index on (001) cleavage fragments, using the determinative curve of Emmons (1953).

The proportions of fine-grained groundmass and megacrysts within a porphyritic pegmatite were determined by a modified Rosiwal method. Traverses on a 1-foot square grid were carried out over an outcrop surface. Megacrysts and groundmass were measured along the traverse lines, and the ratio of the total length of megacrysts to the total length of fine-grained groundmass was taken as an estimate of the ratio of their respective volumes.

Camp Judson Pegmatite

Chemical analyses were made of two composite samples of fine-grained groundmass, one sample from a portion of the pegmatite with more perthite megacrysts than average, and one from a portion with less megacrysts than average.

A Rosiwal analysis across the entire width of the pegmatite showed 23.3 per cent megacrysts and 76.7 per cent fine-grained groundmass for a total traverse length of 312.1 feet.

Table 4 gives the average modal and chemical compositions of the pegmatite.

TABLE 6.—CHEMICAL AND MODAL COMPOSITIONS OF BURNT AREA PEGMATITE

	A Fine-Grained Groundmass		B Megacrysts	C Quartz-Muscovite Pods	D Hanging-Wall	E Footwall	F Total Pegmatite
	Hanging-Wall 146-55	Footwall 136-55					
Chemical Composition (Weight Per Cent)							
SiO_2	72.16	73.49	68.6	81.0	71.8	72.9	72.4
Al_2O_3	15.53	15.62	17.1	13.5	15.9	15.8	15.8
Fe_2O_3	0.58	0.30	..	..	0.36	0.25	0.30
FeO	0.69	0.68	..	..	0.43	0.56	0.50
MgO	0.08	0.07	..	..	0.05	0.06	0.06
CaO	1.10	1.28	..	..	0.65	1.05	0.85
Na_2O	6.40	5.63	2.66	0.21	4.66	5.06	4.86
K_2O	1.24	0.95	11.69	3.68	4.59	2.58	3.58
H_2O^-	0.76	0.89	..	1.58	0.62	0.79	0.70
H_2O^+	0.08	0.10	..	..	..	..	..
TiO_2	tr.	tr.	..	..	..	..	..
P_2O_5	1.11	0.97	..	..	0.69	0.80	0.75
MnO	0.12	0.13	..	..	0.07	0.11	0.09
Li_2O	0.02	0.05	..	..	0.01	0.04	0.02
	99.87	100.16					
Modal Composition (Volume Per Cent)							
Quartz	30.0		5.0	65	25.8	27.5	26.7
Plagioclase	56.4		18.3	..	40.2	49.2	44.7
Microcline	..		76.4	..	22.2	10.7	16.4
Muscovite	11.9		0.1	35	10.6	11.0	10.8
Tourmaline	..		..	..	..	..	..
Garnet	0.1		..	..	0.1	0.1	0.1
Apatite	1.4		..	..	0.9	1.2	1.0

A. Chemical analyses by W. H. Herdsman. Sample 146-55, composite sample from hanging-wall unit; 136-55, composite sample from footwall unit. Modal analyses are of two composite samples with total area of 4500 square mm. Millimeter-grained rock with patchy granoblastic texture. Plagioclase (An_1) grains fractured and strongly strained. Quartz interstitial to plagioclase with slight to moderate strain. Apatite in equant irregular grains of about 1.0 mm.

B. Chemical composition, average of specimens from Burnt Area pegmatite (Table 3), Na_2O and K_2O determined by flame photometer. Al_2O_3 and SiO_2 calculated from mode. Modal composition, average of specimens from Burnt Area pegmatite (Table 3). Blocky microcline perthite crystals 2 to 24 inches. Plagioclase (An_{0-1}) occurs both as oriented lamellae and in irregular grains. Most megacrysts contain graphically intergrown quartz, but about one out of three is free of quartz.

C. Chemical composition calculated from visual estimate of mode. Muscovite contains 0.6 per cent Na_2O and 10.5 per cent K_2O as determined by flame photometer. Modal composition, visual estimate.

D, E. Chemical and modal compositions: compositions from columns A, B, and C combined in proportions of outcrop modal analysis given in Table 5.

F. Chemical and modal composition: total composition of pegmatite calculated on basis of 50 per cent hanging-wall unit and 50 per cent footwall unit.

Burnt Area Pegmatite

Table 5 gives the results of a Rosiwal analysis across the entire width of the Burnt Area pegmatite. Composite samples of fine-grained groundmass were collected for chemical analysis from the footwall and hanging-wall portions of the pegmatite. Table 6 gives the average modal and chemical compositions.

Buell Ranch Pegmatite Complex

By far the greatest mass of pegmatite rock within the complex is classified as homogeneous fine-grained members and layered members, each layered member being subdivided into a footwall fine-grained unit and a hanging-wall porphyritic unit. Table 9 gives chemical analyses of rock samples representing each of the three important types of units, and Table 7 gives modal analyses of a large number of specimens from two types of fine-grained units. A statistical analysis of the modes of Table 7 (Table 8) indicates that there is no significant difference betwee the two types in quartz, muscovite, and total feldspar content but that plagioclase and microcline shown highly significant differences. In Table 9 the average

TABLE 7.—MODAL COMPOSITION OF FINE-GRAINED UNITS, BUELL RANCH PEGMATITE COMPLEX

Sample	Quartz	Microcline	Plagioclase	Muscovite	Biotite	Tourmaline	Apatite	Garnet
Modal Analyses of Fine-Grained Footwall Units (Volume Per Cent)*								
227–55	31.1	0.9	59.6	6.4	2.0	..	..	..
65–56	37.2	1.4	45.7	14.6	0.7	..	0.4	..
97–56	38.5	0.3	48.3	12.4	0.2	..	0.4	..
101–56	39.4	0.2	47.5	11.8	0.6	..	0.3	..
102–56	35.4	2.7	46.3	14.2	1.1	..	0.4	..
106–56	36.1	5.0	52.9	6.0	..	..	0.1	..
108–56	36.0	3.6	47.6	11.4	0.8	0.4	0.4	..
109–56	34.9	4.4	50.6	9.2	..	..	0.1	0.8
122–56	31.4	8.8	48.2	8.0	1.2	2.0	0.4	..
235–55	31.3	4.1	54.4	9.8	0.1	..	0.4	..
233–55	35.3	4.6	45.2	13.4	0.1	1.0	0.3	..
229–55	29.8	3.0	63.2	..	..	3.8	..	..
Average	34.7	3.2	50.8	9.8	0.6	0.6	0.3	0.1
Modal Analyses of Fine-Grained Homogeneous Members (Volume Per Cent)*								
113–56	32.8	10.0	41.6	14.8	0.5	0.2	0.2	..
238–55	30.0	14.8	45.6	9.8	0.3	..	0.1	..
114–56	32.4	12.0	44.9	9.4	0.2	..	..	1.0
78–56	33.4	15.7	38.4	11.6	0.2	0.2	0.5	..
80–56	29.0	15.8	44.6	8.0	..	0.2	0.3	2.4
81–56	32.9	4.8	47.4	13.3	..	1.6	0.2	..
82–56	31.4	13.8	44.6	10.2	..	0.5	0.3	..
83–56	36.8	14.2	28.0	20.6	0.2	0.3	0.1	..
117–56	36.9	10.4	39.6	11.8	..	1.1	0.1	..
237–55	32.0	19.6	36.5	11.2	0.6	..	0.2	..
236–55	33.5	21.7	31.8	12.0	0.7	..	0.2	..
118–56	32.6	7.7	45.6	12.0	..	0.6	0.4	1.0
Average	32.8	13.4	40.7	12.0	0.2	0.4	0.2	0.4

Sample locations shown in Figure 4.

* Each mode is an average of modal analyses performed on two stained thin sections by point counting and represents approximately 3000 points over an area of approximately 2000 square mm.

modal composition of the homogeneous fine-grained units and the footwall fine-grained units is compared with a modified CIPW norm calculated from the chemical analysis of a porphyritic hanging-wall unit. Excess alumina (corundum) in this norm has been converted to muscovite according to the equation

$$\underset{\text{corundum}}{Al_2O_3} + \underset{\text{Or-feldspar}}{KAlSi_3O_8} + H_2O = \underset{\text{muscovite}}{KAl_3Si_3O_{10}(OH)_2}.$$

The only important differences in composition between the three types of units are in the percentages of microcline and plagioclase. The percentages of feldspar in the homogeneous pegmatite members are intermediate between those of the hanging-wall and footwall units.

Chemical compositions of the two types of fine-grained units have been calculated from the average modes, and in Table 9 these are compared with the chemical compositions of individual samples determined by chemical analysis. The compositions of samples 227-55 and 80-56 closely approximate, respectively, the average fine-grained footwall unit and the average fine-grained homogeneous unit.

The compositions of samples 228-55 and 227-55 combined in the proportions 60:40 (representing the average ratio of widths of footwall and hanging-wall units within the complex) have been assumed to represent the average layered member in the complex. This composition, given in Table 9, is close to that of the average homogeneous member.

The compositional differences between the layered and homogeneous members are small, and either composition should provide a good approximation to the average composition of the entire complex. The average of the two units is taken as the best estimate of the over-all composition of the complex.

TABLE 8.—STATISTICAL ANALYSIS OF MODAL ANALYSES OF FINE-GRAINED UNITS

	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square
Quartz	Between types	46.22	1	46.22
	Within types	327.69	22	14.90
	Within specimens	246.02	24	10.25
Microcline	Between types	1176.12	1	1176.12*
	Within types	618.32	22	28.10
	Within specimens	422.83	24	17.62
Plagioclase	Between types	1164.27	1	1164.27*
	Within types	66.04	22	66.04
	Within specimens	28.27	24	28.27
Muscovite	Between types	58.52	1	58.52
	Within types	617.66	22	28.08
	Within specimens	176.55	24	7.36
Total feldspar	Between types	0.17	1	0.17
	Within types	1318.41	22	59.93
	Within specimens	1892.72	24	78.86

* Difference between types significant at 1 per cent level

Harney Peak Granite

The composition of the Harney Peak granite has been determined at two locations (Fig. 1). At the first locality, near "The Needles," the granite has a seriate granoblastic texture with an average grain size of approximately 5 mm. It shows an irregular lamination. Perthite-rich leucocratic layers averaging 10 mm in width alternate with plagioclase-rich muscovite- and garnet-bearing layers. A single large sample weighing approximately 20 pounds was collected at this locality. The modal composition is based on four thin sections cut normal to the layering, and the chemical composition on the entire sample greatly reduced in bulk.

The granite at the summit of Harney Peak is porphyritic with subhedral, blocky graphic granite megacrysts of 1 to 8 inches irregularly distributed through a fine-grained groundmass. The sample representing the fine-grained groundmass consisted of eight chips collected over an area of approximately 50 square feet. The proportions of fine-grained groundmass

TABLE 9.—CHEMICAL AND MODAL COMPOSITIONS OF BUELL RANCH PEGMATITE COMPLEX

	Layered member		C Homogeneous Fine-Grained Members		D Average Fine-Grained Footwall Unit	E Average Fine-Grained Homogeneous Members	F Total Layered Members	G Average of Complex
	A Hanging-Wall Unit 228-55	B Footwall Unit 227-55	80-56	236-55				
Chemical Composition (Weight Per Cent)								
SiO_2	73.82	74.52	74.61	75.56	75.3	74.3	74.28	74.4
Al_2O_3	14.84	15.34	14.84	15.04	14.7	15.4	15.13	15.0
Fe_2O_3	0.09	0.69	0.37	0.24	..	..	0.45	0.44
FeO	0.83	0.66	0.42	0.74	..	..	0.73	0.62
MgO	0.38	0.32	0.05	0.25	..	..	0.34	0.20
CaO	0.64	0.68	0.50	0.86	0.8	0.5	0.66	0.58
Na_2O	3.32	5.48	4.62	3.58	5.7	4.6	4.61	4.62
K_2O	4.96	1.49	3.46	2.96	1.6	3.5	2.88	3.17
Rb_2O	n.d.	n.d.	0.03	n.d.	..	..	..	..
H_2O^+	1.00	0.68	0.61	0.67	0.4	0.5	0.81	0.71
H_2O^-	0.08	0.09	0.05	0.08	..	..	0.09	0.07
TiO_2	tr.	tr.	0.02	tr.	..	..	..	..
P_2O_5	0.13	0.12	0.21	0.14	0.15	0.1	0.12	0.16
MnO	tr.	0.06	0.06	0.03	..	..	0.04	0.05
Li_2O	0.07	0.04	n.d.	0.05	..	..	0.05	0.05
	100.16	100.17	99.85	100.20				
Modal Composition (Volume Per Cent)								
Quartz	32.4	31.1	29.0	33.5	34.7	32.8	33.8	33.3
Plagioclase	30.5	59.6	44.6	31.8	50.8	40.7	42.7	41.7
Microcline	22.7	0.9	15.8	21.7	3.2	13.4	11.0	12.2
Muscovite	11.2	6.4	8.0	12.0	9.8	12.0	10.4	11.2
Biotite	..	2.0	..	0.7	0.6	0.2	0.4	0.3
Tourmaline	..	..	0.2	..	0.6	0.4	0.4	0.4
Apatite	0.3	..	0.3	0.2	0.3	0.2	0.25	0.2
Garnet	..	..	2.4	..	0.2	0.4	0.1	0.2

A. Chemical analysis of sample 228–55 from hanging-wall unit by W. H. Herdsman. Original sample weighed approximately 80 pounds and extended across width of unit. Decimeter-grained rock with porphyritic texture. Graphic granite megacrysts 6 inches and quartz-muscovite cores 2 inches in albite-quartz groundmass. Modal composition, modified norm (excess Al_2O_3 calculated as muscovite) calculated from chemical analysis of 228–55. Normative composition of plagioclase is $An_{7.5}$.

B. Chemical analysis of sample 227–55 from footwall fine-grained unit adjacent to hanging-wall porphyritic unit of A by W. H. Herdsman. Modal analysis of millimeter-grained rock with seriate granoblastic texture. Plagioclase, An_7.

C. Chemical analyses of samples from homogeneous fine-grained members by C. O. Ingamells, Rock Analysis Laboratory, University of Minnesota (80–56) and W. H. Herdsman (236–55). Modal analyses, both samples millimeter-grained rock with seriate granoblastic texture.

D. Chemical composition calculated from average modal composition of footwall fine-grained units (Table 7). Modal composition from Table 7.

E. Chemical composition calculated from average modal composition of homogeneous fine-grained units (Table 7). Modal composition from Table 7.

F. Chemical and modal compositions, total composition of layered member calculated from columns A and B on basis of 40 per cent hanging-wall unit and 60 per cent footwall unit.

G. Chemical composition, average of chemical analysis of 80–56 from column C and total composition of layered member from column F. Modal composition, average of modal compositions from columns E and F.

TABLE 10.—CHEMICAL AND MODAL COMPOSITIONS OF HARNEY PEAK GRANITE

(Weight per cent)

	A	Harney Peak Locality		
	"The Needles" Locality	B Fine-grained groundmass	C Megacrysts	D Total
Chemical Composition (Weight Per Cent)				
SiO_2	74.54	74.2	69.7	73.2
Al_2O_3	14.96	15.6	16.7	15.9
Fe_2O_3	0.25	..	..	..
FeO	0.87	..	..	..
MgO	0.19	..	..	..
CaO	0.72	0.7	..	0.6
Na_2O	4.08	5.9	2.69	5.3
K_2O	3.41	1.7	11.27	3.5
H_2O^+	0.66	0.3	..	0.3
H_2O^-	0.09	..	..	..
TiO_2	0.04	..	..	..
P_2O_5	0.07	..	..	..
MnO	0.09	..	..	..
Li_2O	0.06	..	..	..
	100.03			
Modal Composition (Volume Per Cent)				
Quartz	31.5	30.3	9.4	26.4
Plagioclase	39.5	55.8	22.2	49.4
Microcline	19.9	6.4	66.2	17.8
Muscovite	8.6	6.7	0.8	5.6
Tourmaline	..	0.2	..	0.2
Garnet	0.4	0.7	..	0.6
Biotite	0.1	..	..	0.1
Sample area (mm^2)	3500	4500	4000	

A. Chemical and modal analyses of layered granite at "The Needles" locality. Chemical analysis by W. H. Herdsman. Sample collected at exposure on west side of State Highway 87, 300 feet north-northwest of hairpin turn in SW ¼ of SW ¼ of sec. 28, T. 2 S., R. 5E. Seriate granoblastic texture with average grain size of 5 mm. Irregular lamination of perthite-rich leucocratic layers and plagioclase-rich muscovite-bearing and garnet-bearing layers. Plagioclase, An_{13}.

B. Chemical and modal compositions of fine-grained groundmass of porphyritic granite at Harney Peak locality. Samples collected 100 feet northwest of fire tower on summit of Harney Peak. Chemical composition calculated from mode. and perthite megacrysts were determined by Rosiwal analysis over this same area.

Table 10 gives chemical and modal compositions of the granite at each locality.

DISCUSSION

Table 11 summarizes compositional data for the three pegmatites and the two locations within the Harney Peak granite. The compositions at each of these widely separated localities are very similar.

In Figure 9 the modal compositions given in Table 11 have been plotted on the liquidus of the "synthetic-granite" system at 2000 bars H_2O. All the compositions fall near the quartz-feldspar field boundary and within a "thermal trough" outlined by the 740° C. isotherm. Increasing the H_2O pressure to 3000 bars moves the field boundary 3 per cent away from the quartz corner, and decreasing the H_2O pressure to 1000 bars moves it 3 per cent toward the quartz corner. The percentage of Or at the granite minimum remains nearly constant at 25 per cent (Tuttle and Bowen, 1958).

A magmatic theory of origin appears to offer the most reasonable solution to the problem of how rock bodies of nearly identical bulk compositions could be emplaced in widely separated localities, and it is in harmony with the transgressive character of the pegmatites. This theory calls for the rock masses to have been derived from a common source of uniform composition, to have been intruded as silicate melts, and to have crystallized in a system closed except for a minor amount of assimilation of wall rock and the escape of volatile gases.

Although the compositions which have been determined at two localities within the Harney Peak granite are hardly enough to characterize the entire mass, they suggest that the granite does not differ greatly in composition from the unzoned pegmatites in the surrounding schist. Both the granite and pegmatites have reached

Modal composition average of modal analyses of eight samples. Seriate granoblastic millimeter-grained texture. Plagioclase, An_{10}.

C. Chemical and modal compositions of perthite megacrysts in porphyritic granite at Harney Peak locality. Average of two samples from Table 3.

D. Total chemical and modal composition of porphyritic granite at Harney Peak locality calculated from columns B and C on basis of outcrop modal analysis which showed 19.0 per cent perthite megacrysts and 81.0 per cent fine-grained groundmass over a total traverse length of 60.8 feet.

approximately the same stage of differentiation with respect to the "synthetic-granite" system (Fig. 9). If the experimental data are applicable, and Brobst (in press) have determined the compositions of two well-known zoned pegmatites, the Peerless and the Hugo. The Peerless is

TABLE 11.—CHEMICAL AND MODAL COMPOSITIONS OF PEGMATITES AND GRANITE, KEYSTONE DISTRICT, SOUTH DAKOTA

(Weight per cent)

	A Camp Judson Pegmatite	B Buell Ranch Pegmatite Complex	C Burnt Area Permatite	Harney Peak Granite	
				D Harney Peak	E "The Needles"
Chemical Composition (Weight Per Cent)					
SiO_2	73.9	74.4	72.4	73.2	74.54
Al_2O_3	15.4	15.0	15.8	15.9	14.96
Fe_2O_3	0.58	0.44	0.30	..	0.25
FeO	0.52	0.62	0.50	..	0.87
MgO	0.06	0.20	0.06	..	0.19
CaO	0.62	0.58	0.87	0.6	0.72
Na_2O	4.53	4.62	4.86	5.3	4.08
K_2O	3.74	3.17	3.58	3.5	3.41
H_2O	0.35	0.71	0.70	0.3	0.66
TiO_2	..	..	tr.	..	0.04
P_2O_5	0.17	0.16	0.75	..	0.07
MnO	0.02	0.05	0.09	..	0.09
Li_2O	0.03	0.05	0.02	..	0.06
Modal Composition (Volume Per Cent)					
Quartz	29.0	33.3	26.7	26.4	31.5
Plagioclase	44.3_{An_4}	$41.7_{An_{5-7}}$	$44.7_{An_{0-1}}$	$49.4_{An_{7-11}}$	$39.5_{An_{13}}$
Microcline	20.1	12.2	16.4	17.8	19.9
Muscovite	2.9	11.2	10.8	5.6	8.6
Biotite	..	0.3	..	0.1	0.1
Tourmaline	2.6	0.4	..	0.2	..
Garnet	0.2	0.2	0.1	0.6	0.4
Apatite	0.2	0.2	1.0	..	..

the pegmatites which have been investigated should not be thought of as differentiates of the granite but rather as rock bodies which were at a similar stage of differentiation. Not only do the compositions appear to be the same, but there are no obvious textural criteria to distinguish between the unzoned pegmatites and the granite. The distinction between the two is essentially one of size and configuration of the rock bodies.

Whether the concentrically zoned pegmatites in the Keystone district have compositoins similar to the unzoned pegmatites is not known, but it appears likely that there is considerable individual variation from pegmatite to pegmatite. Sheridan *et al.* (1957) and Norton, Page, considerably richer in quartz and poorer in microcline than the pegmatites determined here, whereas the Hugo has a very similar composition although slightly richer in quartz. There are several lithium-rich pegmatites in the area which are said to contain up to 10 or 20 per cent spodumene, and the bulk compositions of these pegmatites must differ significantly from those determined here.

Application of laboratory data on synthetic systems to natural rocks is uncertain, particularly when crystallization of ternary feldspars is involved. Tuttle (1952) has suggested, on the basis of experimental work in the "synthetic-granite" system, that a great many plutonic rocks of granitic composition have crystallized

within the field of a single feldspar. Laboratory investigations in the ternary-feldspar system (Yoder, Stewart, and Smith, 1956), however, have shown that the addition of a few per cent anorthite raises the crest of the solvus between K-rich feldspar and plagioclase by a large amount and that two feldspars might reasonably be expected to crystallize from granitic melts containing a small amount of anorthite.

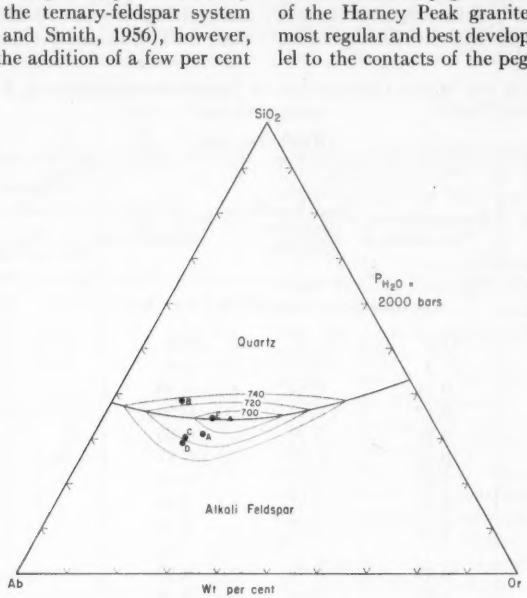

FIGURE 9.—MODAL COMPOSITIONS OF GRANITE AND PEGMATITES PLOTTED ON LIQUIDUS OF SYNTHETIC-GRANITE SYSTEM

Liquidus data after Tuttle and Bowen (1958). Muscovite and accessory minerals have been eliminated and plagioclase is plotted as Ab. A, Camp Judson pegmatite. B, Buell Ranch pegmatite complex. C, Burn Area pegmatite. D, Harney Peak granite, Harney Peak. E, Harney Peak granite, The Needles. Solid triangle, "granite minimum."

Whether primary crystallization is of the one- or two-feldspar type, the bulk compositions shown in Table 11 require that it start with quartz and a Na-rich feldspar. If crystallization takes place in the two-feldspar field a granite minimum liquid will form, and two feldspars plus quartz will eventually crystallize together; K-rich feldspar will unmix as a separate phase only after the rock is entirely solid if it crystallized in the one-feldspar field.

Some conclusions concerning the sequence of crystallization in the pegmatites can be drawn from certain structural and textural features, especially laminations, perthite megacrysts, and phantom laminations.

Laminations, particularly tourmaline-rich laminations, are a major textural and structural feature of all the pegmatites studied, as well as of the Harney Peak granite. Where they are most regular and best developed, they are parallel to the contacts of the pegmatite. They cannot be regarded as a border phase of the pegmatite because they occur across the entire width of the Camp Judson pegmatite. Nor can they be inherited from country rock which has been replaced by pegmatite, for in the Camp Judson pegmatite they transect both the bedding and schistosity of the country rock. In the Harney Peak granite, laminations adjacent to inclusions of country rock are invariably parallel to the contact of the granite and schist, regardless of the orientation of the schistosity in the inclusion. The nearly vertical dips of many of the pegmatites in which laminations occur preclude the possibility that the laminations represent rhythmic gravitational settling of crystals as has been proposed for many banded igneous complexes. Whatever their origin, the laminations are almost certainly a primary structure of the granitic rock which formed as the rock crystallized from the melt.

J. A. Redden (1955, Ph.D. thesis, Harvard Univ.) and Staatz and Trites (1955) have pro-

posed that "phantom laminations" have formed as a result of contemporaneous crystallization of laminated groundmass and perthite megacrysts. According to this view, the tourmaline or garnet grains which mark a particular lamination originally crystallized on the surface of perthite megacrysts and became included in the megacrysts as a result of continued crystallization of alkali feldspar on the same surface.

An alternative explanation for "phantom laminations" is that fine-grained laminated groundmass began to crystallize first, followed by perthite megacrysts which grew, at least in part, by replacement of fine-grained material. In accordance with this view, phantom laminations represent relict minerals from the groundmass (principally tourmaline) which were especially resistant to replacement.

Textural relationships between fine-grained groundmass and perthite megacrysts are ambiguous concerning crystallization sequence. The commonly observed irregular and gradational contacts between perthite megacrysts and fine-grained groundmass are consistent with either simultaneous crystallization or later replacement of fine-grained material by perthite. If the assumption is made that the laminations in the fine-grained groundmass originally crystallized as regular coherent layers, however, the structural relationships between perthite megacrysts and laminated groundmass do indicate something concerning their crystallization sequence. The "breccia" structure illustrated in Figure 3 in which contorted patches of laminated rock are crowded between perthite megacrysts would then indicate that the megacrysts as they grew have disrupted and pushed aside material which was at least partly crystalline. Contemporaneous crystallization, in part, is not contradicted by these relationships and is to be expected if K-rich feldspar crystallized from a rest liquid of granite-minimum composition in the two-feldspar stability field since quartz and plagioclase would simultaneously crystallize in the eutectic proportions.

Whether the megacrysts have crystallized from a residual melt of approximately the granite-minimum composition or porphyroblastically after unmixing of a single alkali feldspar cannot be decided at present on the basis of either laboratory or field data. The tendency for microcline to form large porphyroblasts in metamorphic rocks is well known, and the large size of the perthite crystals is not necessarily evidence for crystallization from a melt.

The origin of many features of the Buell Ranch pegmatite complex is not well understood at present. It seems worthwhile, however, to discuss some of the more puzzling aspects and attempt to define the circumstances under which intrusion and crystallization may have taken place.

Every member of the complex, whether layered or homogeneous, is bounded above and below by a schist parting, and all appear to have approximately the same bulk composition. The map of the complex reveals a close and consistent relationship between porphyritic members and schist partings; differentiation into the microcline-rich hanging-wall units and microcline-poor footwall units must have taken place essentially *in situ*, probably without significant additions or subtractions of material from outside each individual member.

Origin of the complex by a solid diffusion or granitization process seems out of the question. If layers within the schist have been granitized because of unusual composition which made them particularly susceptible to replacement or recrystallization, some indication of such layers in their original form should be found outside the complex. If it is ordinary quartz-mica schist that has been granitized, it is incongruous to find essentially unchanged schist partings in the midst of the complex.

Possibly hydrothermal or solid-state metasomatic replacement processes operated after magmatic intrusion and crystallization had taken place, but it is difficult to understand how they could produce either the compositional differentiation or structural relationships so characteristic of the layered members. The quartz-rich fracture fillings, however, may have formed in this way. Their structural situation suggests that the fractures have formed as a result of boudinage deformation of a brittle slab enclosed in more plastic schist. The schist "rolls" (Fig. 8) which penetrate the fractures demonstrate that the fracture fillings crystallized in a low-pressure volume relative to the surrounding rocks. Such a volume will be a site for concentration of relatively mobile material derived from the surrounding rocks. The compositions of the fillings do not suggest crystallization from a silicate melt, and the quartz and perthite may well have been introduced by a hydrous solution, the immediate source of these minerals being the adjacent pegmatite and schist.

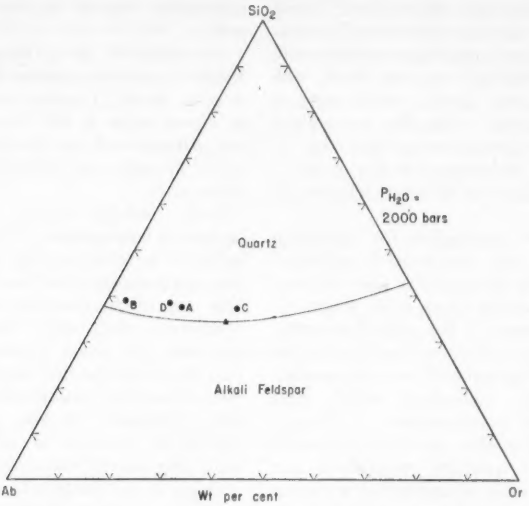

FIGURE 10.—MODAL COMPOSITIONS OF UNITS WITHIN BUELL RANCH PEGMATITE COMPLEX PLOTTED ON LIQUIDUS OF SYNTHETIC-GRANITE SYSTEM

Liquidus data after Tuttle and Bowen (1958). Muscovite and accessory minerals have been eliminated and plagioclase is plotted as Ab. A, homogeneous fine-grained unit. B, footwall fine-grained unit. C, hanging wall porphyritic unit. D, total layered unit. Solid triangle, "granite minimum."

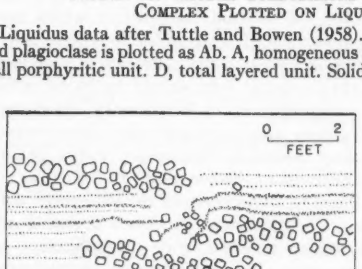

FIGURE 11.—PORPHYRITIC UNIT WHICH CUTS ACROSS SERIES OF TOURMALINE-BEARING LAMINATIONS

Plan view

In Figure 10 the modal compositions of the hanging-wall and footwall units and the bulk composition of the complex are plotted on the liquidus of the synthetic-granite system at 2000 bars H_2O. The hanging-wall unit falls near the "granitic minimum" and the footwall unit near the Ab—SiO_2 join. These compositions are compatible with the course of crystallization expected of a melt crystallizing in the two-feldspar field and might be produced by segregation of "granite-minimum" liquid from the early crystallizing phases.

Structural evidence showing the sequence of crystallization of units within a layered member has been found at one locality. Within a member near the western border of the complex a porphyritic unit cuts across a series of laminations in a fine-grained unit and produces local displacement and deformation of the laminations (Fig. 11). It can be inferred here that the material which forms the prophyritic microcline-rich unit was still mobile when the laminated fine-grained groundmass had consolidated.

The other pegmatites studied do not show differentiation into microcline-rich and microcline-poor units comparable to the layered members in the Buell Ranch complex. The Burnt Area pegmatite, however, is distinctly richer in microcline in its hanging-wall portion than in its footwall portion, and this may be the result of an imperfectly operative fractional crystallization process.

The consistent position of the porphyritic units at the hanging wall of each member is not easily explained. Perthite-rich units are also common in the upper portions of many concentrically zoned pegmatites (*See* Cameron *et al.*, 1949, p. 48), and processes similar to those in the layered pegmatites may have operated

here. The process that produced the Buell Ranch complex has generated sharp compositional differentiation within sheets of rock a few feet thick. It is unlikely, however, that it has moved rock material very far, for the transfer of a large amount of material, whether as liquid, crystals, or clouds of ions, moving upward or downward along the schist partings would very likely destroy the striking evidence of sharp but local compositional differentiation.

Gravitational crystal settling has been considered as a mechanism, but the steep dip of the members seems to preclude this. The possibility that the original dip of the pegmatite member was much gentler and that later deformation produced the present steep dips cannot be completely ruled out. Staatz and Trites (1955), however, have described numerous layered pegmatites of widely variable dip and strike in the Quartz Creek district, Colorado; in these a perthite-rich unit occurs on the hanging-wall side of each body.

Rafting of early formed Or-rich feldspar crystals does not seem likely since compositional data indicate that Or-rich feldspar should begin to crystallize after quartz and plagioclase, and the density relationships are not consistent with a rafting mechanism since K-rich feldspar crystals would be denser than the melt from which they crystallized.

A complete theory of origin must explain three important features of the complex: first, the presence of both layered and homogeneous members which have similar bulk compositions; second, the pairing of aplitic quartz-plagioclase and porphyritic "granite-minimum" units within the layered members; third, the invariable hanging-wall position of the porphyritic units. A magmatic theory which involves segregation of early formed crystals from a "granitic-minimum" rest liquid is consistent with the compositional data but does not provide a mechanism by which the consistent and persistent spatial relationships of the units can be explained.

Unusual mineralizers or unusual bulk compositions have commonly been called upon to explain chemical differentiation within zoned pegmatites. In the Buell Ranch pegmatite complex it is clear that chemical differentiation has taken place within granitic rocks which contain only common minerals and which have a perfectly ordinary bulk composition. The process which has operated here might be expected to be active in other localities. Nonconcentrically zoned pegmatites which show similar differentiation into microcline-rich upper units and plagioclase-quartz lower units have been described from southern California (Jahns and Wright, 1951), the Quartz Creek district, Colorado (Staatz and Trites, 1955), and western Connecticut (Gates, 1954) and are much commoner than is ordinarily supposed.

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CORRELATION OF THE CRETACEOUS FORMATIONS OF THE PACIFIC COAST (UNITED STATES AND NORTHWESTERN MEXICO)

BY W. P. POPENOE, R. W. IMLAY, AND M. A. MURPHY

ABSTRACT

This paper includes a discussion of the historical development of stratigraphic classification of Cretaceous rocks on the Pacific Coast of the United States, a summary of the faunal evidence for correlating the Cretaceous rocks with the European stages, and all the stratigraphic and faunal data available for 61 areas along the Pacific Coast in Washington, Oregon, California, and northwest Mexico. Many of these data, particularly for Washington and Oregon, have not been published previously. The chart includes lists of fossils that are most useful stratigraphically and presents correlations with British Columbia, Japan, and the western interior of the United States. Included are maps that show the general distribution of Cretaceous rocks along the Pacific Coast. Such maps for Oregon and Washington show occurrences that are not shown on any other published maps.

CONTENTS

TEXT

	Page
Introduction	1491
Acknowledgments	1492
Historical development of Cretaceous stratigraphic and biostratigraphic classification on the Pacific Coast. By W. P. Popenoe	1492
California	1492
Oregon and Washington	1502
Correlations with the European stages	1504
Berriasian	1504
Valanginian	1505
Hauterivian	1506
Barremian	1508
Aptian	1508
Albian	1509
Cenomanian	1510
Turonian	1510
Coniacian	1512
Santonian	1513
Campanian	1513
Maestrichtian	1516
Correlation of foraminiferal with molluscan zones	1516
Annotations	1517
References cited	1535

ILLUSTRATIONS

Figure	Page
1. Index map of Baja California and western Sonora	1494
2. Index map of California	1495
3. Index map of southwestern Oregon	1500
4. Index map of central Oregon	1502
5. Index map of northwestern Washington	1503

Plate	Facing Page
1. Correlation of the Cretaceous formations of the Pacific Coast of the United States and of northwestern Mexico (Chart 10e of series)	1491

INTRODUCTION

This is Number 10e of a series of correlation charts of North American sedimentary formations prepared by the Committee on Stratigraphy of the National Research Council (Dunbar, 1942).

Preparation of the chart by W. P. Popenoe has been a continuing project for 12 years, and he takes primary responsibility for the columns dealing with California and for correlations based on gastropods and pelecypods. Since 1955 he has been assisted by R. W. Imlay who is mainly responsible for the columns dealing with Oregon and Washington and for correlations based on ammonites. Michael A. Murphy has furnished details concerning the faunal succession of the Lower Cretaceous strata in western Shasta County from the zone of *Hertleinites aquila* to the top of the Albian. The chapter dealing with History of Classification was prepared entirely by W. P. Popenoe.

With the research on Cretaceous rocks and fossils now in progress in the Pacific Coast States, this correlation chart will be out of date as soon as published. Nevertheless it should

serve as a summary of the facts available until the date that it was submitted for publication and should save other geologists considerable time now spent in reviewing publications. One of its main uses will be to indicate the areas or problems that are most in need of research.

Fossil collections at the various institutions are recorded herein as follows: CIT for California Institute of Technology, UCLA for University of California at Los Angeles, UC for University of California at Berkeley, LSJU for Leland Stanford Junior University, CAS for California Academy of Sciences, UW for University of Washington, and USGS for United States Geological Survey.

Acknowledgments

Compilation of the data and maps accompanying this correlation chart required the help of many geologists and institutions. For the State of Washington, Wilbert R. Danner furnished information concerning the Cretaceous of the area east of Everett, Peter Misch of the area north of Mount Baker, Julian Barksdale of the Methow Valley and Harts Pass area, and V. Standish Mallory of the San Juan Islands. In addition, Mallory made available for study the Cretaceous collections in the Museum of Paleontology at the University of Washington as well as many Master of Science theses that contain pertinent information. A map showing the distribution of Cretaceous rocks in Washington was furnished by the Chief of the Washington State Geological Survey at the request of Albert C. Weissenborn, U. S. Geological Survey.

For the State of Oregon Don Wilkinson of Oregon State College and Tom Thayer of the U. S. Geological Survey furnished maps showing the distribution of Cretaceous rocks in central Oregon. Francis Wells of the U. S. Geological Survey furnished a map of southwestern Oregon from which the distribution of Cretaceous rocks was compiled. David Jones of the U. S. Geological Survey furnished pertinent data on the fossils from the Medford-Ashland-Jacksonville area. Hollis Dole of the Oregon State Department of Geology and Mineral Industries along with Francis Wells personally conducted Imlay to most of the important Cretaceous exposures in southwestern Oregon and have shown a keen interest in the stratigraphy and correlations of the Cretaceous rocks. The geologists of the Humble Oil Company have furnished fossil collections that have been useful in making correlations and have pointed out the presence of Cretaceous rocks in certain areas that had not been recorded previously.

For the State of California many thanks for the privilege of examining various Cretaceous fossil collections are due Leo Hertlein and Dallas Hanna of the California Academy of Sciences, Siemon Muller of Leland Stanford Junior University, and J. Wyatt Durham of the University of California at Berkeley. David Jones of the U. S. Geological Survey contributed information concerning the Yreka-Hornbrook area of Northern California. Peter Rodda, Texas Bureau of Economic Geology, furnished data on the Upper Cretaceous rocks of western Shasta County. LouElla Saul, University of California at Los Angeles, furnished much data on the stratigraphy and fossils of the Chico Creek area. Stuart Chuber discussed the Cretaceous rocks of the Fruto quadrangle on the west side of the Sacramento Valley. The geologists of the California Division of Mines furnished a map of California showing the distribution of Cretaceous rocks. The geologists of the Humble Oil Company have given much advice concerning the distribution and correlations of Cretaceous rocks in California.

Special mention should be made of the aid given by Tatsuro Matsumoto of Kyushu University, Japan, during his sojourn in the United States during 1957 and 1958. Throughout the text many references are made to his fossil and age determinations. As a result of his studies, correlations of Cretaceous deposits of the Pacific Coast with the standard sections in Europe are now on a sound basis. Among his many contributions which are reflected by changes in the correlation chart, probably the most important are the recognition of Santonian fossils in the sections on Chico Creek and in the Redding area and the assignments of the *Submortoniceras* and *Metaplacenticeras* beds to the middle and late Campanian respectively.

Historical Development of Cretaceous Stratigraphic and Biostratigraphic Classification on the Pacific Coast

By W. P. Popenoe

California

A little more than 100 years ago, J. B. Trask (1856, p. 85; 1873, p. 92–93) published the first evidence of the occurrence of Cretaceous rocks in California. He described *Ammonites chi-*

coensis and *Baculites chicoensis* from sandstone cropping out in the gorge of Chico Creek, northeast of Chico in Butte County, and referred the containing rocks to the Miocene, because he thought that some of the associated gastropod and pelecypod species belonged to the same genera that today are found living along the coast. He stated further without explanation that the Chico Creek fossils were clearly younger than collections from Ocoya Creek, Tulare County, that had been pronounced Miocene by T. A. Conrad. Additional material from Chico Creek, collected in 1856 by W. P. Blake, was studied by J. S. Newberry and F. B. Meek (*in* Newberry, 1856, p. 24–25), who, without categorically denying Trask's conclusion, suggested that the Chico Creek beds were much more probably Cretaceous in age.

In 1864, the first volume issued by the Geological Survey of California, *Paleontology of California, volume 1*, appeared. This contained descriptions of many Cretaceous species by William More Gabb, paleontologist to the Survey, and a foreword by the Director, Prof. J. D. Whitney, in which a tentative biostratigraphic division into Cretaceous A and B was presented. Cretaceous A was considered the time equivalent of the Ft. Pierre shale of Meek and Hayden; Cretaceous B was correlated with the Fox Hills sandstone. Local sections including the rocks of these divisions were described in some detail in *Geology of California, volume 1*, published in 1865.

T. A. Conrad (1865, p. 362–365) reviewed Gabb's work and pointed out the unmistakably Eocene character of the Cretaceous B fauna, thereby precipitating a controversy with Gabb (1867, p. 226–229; 1866, p. 87–92; Conrad, 1866, p. 97–100; 1867, p. 376–377; 1870, p. 275) that outlived both controversialists and was conclusively settled by T. W. Stanton in 1895.

In the *Paleontology of California, volume 2*, Professor Whitney (*in* Gabb, 1869, p. xii–xiv) classified the Cretaceous rocks into four groups according to Gabb's current views, in descending order, Tejon, Martinez, Chico, and Shasta. The Tejon group included most of the Cretaceous B of Gabb's earlier classification; the Martinez group included a part of Cretaceous B and was considered to rank possibly only as a subdivision of the Tejon; the Chico group was essentially the equivalent of Gabb's earlier Cretaceous A; and the Shasta group comprised those Cretaceous beds older than Cretaceous A and was held to be approximately time equivalent to the European Cretaceous from "Gault to Neocomian inclusive."

From 1869 to 1885 no results were published dealing with new field investigations on the California Cretaceous. The age of Gabb's Chico, Martinez, and Tejon groups was discussed, however, by J. D. Dana (1875, p. 457, 458, 491, 508), Jules Marcou (1876, p. 387), and Angelo Heilprin (1882, p. 196–214); all agreed that the Tejon and Martinez groups were probably of Tertiary age. Marcou argued for a Tertiary age for the Chico group, as well.

In 1885, George F. Becker and C. A. White of the U. S. Geological Survey began publication of a series of papers dealing with the subdivisions of the Pacific Coast Cretaceous strata. White (1885a, p. 11–15) reviewed the faunal and field evidence; he concluded that the Tejon is Eocene, the Chico similarly unquestionably Cretaceous, and that the two groups were part of an unbroken and conformable succession of beds representing continuous deposition that persisted from Cretaceous to Miocene time. Becker (1888, p. 213–218) accepted White's conclusions and suggested a division of the Shasta group into two series. The lower division, characterized by the presence of the pelecypod *Aucella* (*Buchia* of present-day usage), was named the Knoxville series; the upper division was named the Horsetown series. An additional "series," called the Wallala, represented by beds along the Mendocino coast and at Todos Santos Bay, Baja California, was characterized by the aberrant pelecypod *Coralliochama*. The Wallala was considered to be younger than Horsetown and older than Chico. Knoxville and Horsetown were the presumed equivalents of the Neocomian and Gault respectively. This biostratigraphic division was repeated and elaborated in other publications up to about 1891.

In 1883, J. S. Diller of the U. S. Geological Survey began work, under the leadership of Capt. C. E. Dutton, on the geology of the Cascade and Siskiyou mountains of California and Oregon and later extended his investigations to adjacent regions of the northern Sacramento valley and the northern Sierra Nevada. In the latter part of Diller's investigations in California he was joined in 1893 by T. W. Stanton, paleontologist with the U. S. Geological Survey, who continued to work in California until 1902, although much of his later work was not published. The publications (Diller, 1889; 1890; 1891; 1893; 1895; Diller and Stanton, 1894; Stanton, 1893; 1895; 1896) resulting from this work described the areal

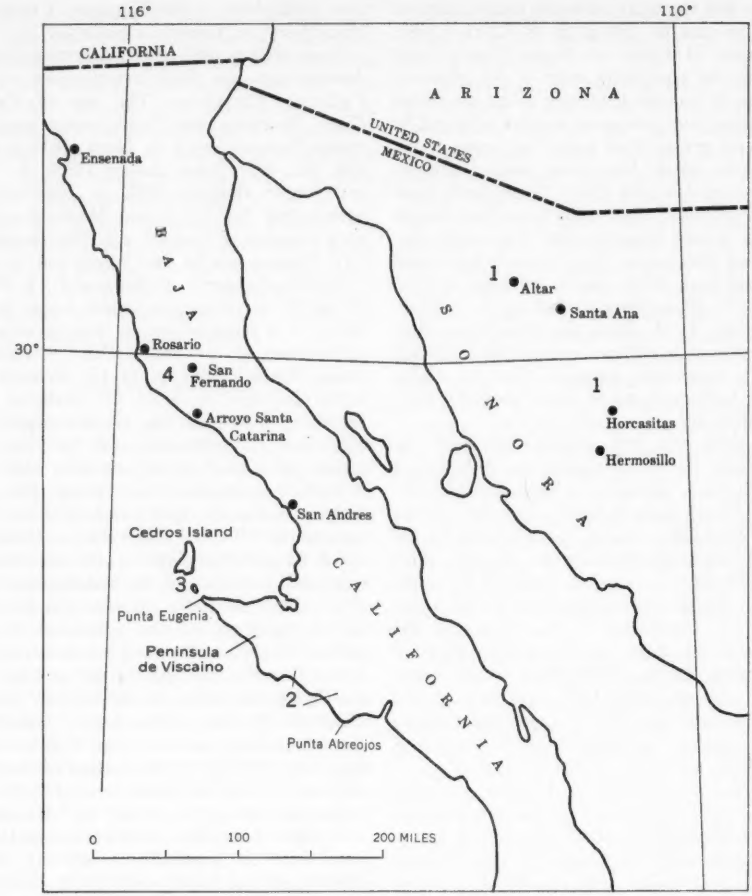

FIGURE 1.—INDEX MAP OF BAJA CALIFORNIA AND WESTERN SONORA
Showing positions of numbered columns 1 to 4 on Plate 1

extent, faunas, and stratigraphy of the Cretaceous rocks in a number of localities in middle and northern California. These papers, beside adding to the precise knowledge of the Cretaceous rocks of these regions, showed that the Tejon and Martinez groups of Gabb are clearly of Tertiary age; that Gabb's mistaken conclusions probably resulted from errors of commission in collecting, segregating, and identifying his faunas; and that the contact between "Chico" and "Tejon" was disconformable or unconformable wherever observed and represented a faunal and stratigraphic hiatus including highest Cretaceous and in some places lowest Tertiary beds. Diller's (1906) concluding contribution to this study described the overall distribution of Cretaceous strata north and east of Redding in Shasta county but recognized no rock subdivisions within the system.

During approximately the same period of Diller's work, H. W. Fairbanks was studying the geology of the California Coast Ranges south of San Francisco. He showed that Cretaceous rocks are much more widely distributed in this region than had been realized hitherto. Although most of his published work was not accompanied by geologic maps, the San Luis

FIGURE 2.—INDEX MAP OF CALIFORNIA

Showing distribution of Cretaceous strata and position of numbered columns 5 to 43 on Plate 1. Solid black—normal Cretaceous sedimentary rocks. Pattern—Franciscan formation

Obispo folio, published in 1904, contains the most detailed map of Cretaceous formations published up to that time.

Meanwhile systematic paleontological work on Cretaceous faunas lagged. As late as 1900, Gabb's work in volumes 1 and 2 of the *Paleontology of California* was still the principal reference in this field. Stanton (1895) published an excellent description of the Knoxville fauna, and Stanton (1896), White (1885b;

1889), and J. G. Cooper (1894; 1897) described new species; but these papers did not greatly increase knowledge of the occurrence or stratigraphic distribution of the species described.

In summary, by 1900, most of the major occurrences of Cretaceous strata were known, and some broader lithologic subdivisions had been recognized. The faunas, although known to be large, were very inadequately described. Detailed stratigraphic and zonal paleontologic knowledge was almost lacking, and few Cretaceous areas had been shown upon published geologic maps.

Frank M. Anderson (1902) attempted a synthesis and correlation of what was known of the Pacific Coast Cretaceous faunas and formations. This work, notable as being the most comprehensive study undertaken of the Cretaceous since Gabb's time, included descriptions of many new species, principally of ammonites; faunal lists from numerous localities; description of a new faunal division of the "Knoxville" series called the Paskenta beds; a division of the Pacific Coast Upper Cretaceous into "Upper Chico" and "Lower Chico"; and a correlation chart in which the Pacific Coast Cretaceous divisions were correlated with the Cretaceous of the eastern United States, India, and Europe. This was the first published attempt to subdivide the entire Pacific Coast Cretaceous strictly on faunal grounds and to correlate the subdivisions with the Stages of the standard European section.

About 1901, the U. S. Geological Survey commenced a series of investigations and publications of the geology of California Coast Range oil fields. The work, originally planned and prosecuted by George H. Eldridge, was continued after Eldridge's death in 1905 by a succession of able workers including Ralph Arnold, Robert Anderson, Harry Johnson, Walter English, R. W. Pack, W. S. W. Kew, Harold Hoots, W. P. Woodring, Ralph Stewart, and others. The resulting geologic maps published in Survey bulletins and professional papers showed the areal extent of a number of Cretaceous outcrops with a precision and skill not approached before in publication and not always equalled since. The Cretaceous rocks at that time were thought to offer slight promise of oil production; for this reason little attention was paid in these reports to working out the detailed stratigraphy and paleontology of the system, or to defining and naming new rock or faunal units. A notable exception is in the work of Robert Anderson and R. W. Pack (1915), who described the geology of the formations cropping out along the west border of the San Joaquin valley north of Coalinga. The name "Panoche formation" was applied to a very thick sequence of sandstone, conglomerate, and shale forming the lower of two major subdivisions of the Upper Cretaceous; the overlying succession of "chocolate" shales at the top was named the "Moreno formation". Anderson and Pack collected considerable numbers of fossils from these two formations, but these unfortunately were never identified and described in publication.

The California oil bulletins of the U. S. Geological Survey contributed little to published knowledge of refined Cretaceous stratigraphy and zonal paleontology or to data that would forward regional correlation of Cretaceous exposures in different parts of the State. They did, however, furnish accurate maps of large and important areas of Cretaceous rocks which had been previously poorly known.

The period from 1902 to 1926 was one of relative inactivity in stratigraphic and biostratigraphic work in the California later Mesozoic; most of the attention during this quarter century was paid to studies of Tertiary formations and faunas. Arnold (1908) described a few species from the Santa Cruz area; J. P. Smith (1916) stated that "The California Upper Cretaceous is divisible into two parts—Lower Chico, characterized by '*Schloenbachia*' (= *Subprionocyclus*) and Upper Chico characterized by the presence of '*Placenticeras*' (= *Metaplacenticeras*)," an observation that was ahead of its day in the recognition of two important and extensive ammonite zones. E. L. Packard (1916) subdivided the Cretaceous beds of the Santa Ana Mountains of southern California on both a lithologic and faunal basis, described four faunal zones, and attempted to correlate these with the "Horsetown" beds near Redding in Shasta County and with the Chico Creek beds of Butte County. This was the first attempt to subdivide and correlate in detail a fossiliferous Cretaceous section in California. In a later paper, Packard (1922) described a considerable number of new molluscan species from the Santa Ana Cretaceous fauna. C. A. Waring (1917) described the general occurrence of Cretaceous rocks in the Santa Monica Mountains and Simi Hills of southern California, described a few new molluscan species, and listed Cretaceous faunas from three localities. Those from the Simi Hills were later cited by Kew (1924, p. 11–13).

Notwithstanding the contributions of White,

Stanton, Cooper, Anderson, Arnold, Packard, and Waring, Gabb's work in the *Paleontology of California* remained the principal reference for Pacific Coast Cretaceous faunas as late as 1925. Gabb, however, did not designate either types or type localities for his new species—two omissions that, because of the rather uniform character of the faunas, led to widespread confusion as to the identity and stratigraphic positions and ranges of the described species. This situation was largely remedied by R. B. Stewart, who, about 1924, undertook to restudy that part of Gabb's type material that was housed in the Museum of the Academy of Natural Sciences at Philadelphia and in the Museum of Comparative Zoology at Harvard University. Stewart (1926; 1930) named holotypes and lectotypes for many of Gabb's species, re-illustrated them, and established type localities wherever these were determinable. Stewart had little first-hand knowledge of the field or stratigraphic relations of the fossil material studied, hence in a few cases did not recognize some of the stratigraphic errors in Gabb's work and came to incorrect conclusions regarding the ages of certain species. His work from the paleontologic angle, however, was critical, shrewd, and profound and is of the first importance in fixing the specific character and helping to determine the stratigraphic position and range of many of Gabb's species.

The decade from 1930 to 1940 was all but monopolized by the publications of F. M. Anderson, who re-entered the Cretaceous field following retirement from a career as consultant. Anderson (1931a) referred the Cretaceous beds cropping out in Siskiyou County to the "Middle and Upper Chico"; these were believed to be Middle Turonian to Early Senonian in age; this was followed (Anderson, 1932) by a discussion of the "Knoxville-Shasta" succession in California. The lower Knoxville of Becker and Stanton was assigned to the Jurassic, the upper Knoxville, or "Paskenta beds", to the Infra-Valanginian and Valanginian; the Horsetown division of the Shasta series was stated to range in age from Hauterivian to Albian inclusive; and a succession of faunal zones was set up, largely on the basis of occurrence of the pelecypod *Buchia* [*Aucella*] and certain ammonites. In a later paper (Anderson, 1933) these conclusions were amplified. Finally (Anderson, 1938b) appeared a comprehensive paper in which nearly all Lower Cretaceous occurrences on the Pacific Coast were discussed and correlated, nearly 300 species, mainly of mollusks, were described and figured, and a classification of the local Lower Cretaceous or "Shasta Series" on a zonal and stage basis was presented.

Before 1935, very little attempt appears to have been made to subdivide the Upper Cretaceous sequence on the Pacific Coast either stratigraphically or biostratigraphically, except for the rather vague and uncertain subdivisions of "Upper Chico" and "Lower Chico" mentioned above. In 1935 appeared two papers in which the first of several subdivisions were proposed. Taff (1935) in describing the stratigraphy and structure of the Mt. Diablo area divided the Upper Cretaceous series into three formations, in ascending order, Chico, Panoche, and Moreno. The Chico and Panoche formations of Taff are together the approximate equivalent of the Panoche formation of Anderson and Pack. On the basis of the occurrence of fossiliferous "Chico" boulders included in the basal part of the restricted Panoche formation, the Panoche was held to be younger than the "Type Chico" (of Chico Creek?), a conclusion that has not been upheld by later work. Anderson and Hanna (1935) in a discussion of the Cretaceous rocks of Baja California, compared these with the inferred equivalents in the Mt. Diablo section as described by Taff, as well as with some other California occurrences. From the correlation chart accompanying this paper, one may conclude that the authors considered that the fauna of the "Type Chico" (of Chico Creek?) is Cenomanian and Turonian in age; that the Punta Banda beds containing *Coralliochama orcutti* (= the Wallala formation of White) are not older than Late Turonian; and that the uppermost Cretaceous strata of the Santa Ana Mountains and the beds of the Catarina formation of Baja California are approximately correlative and are Late Campanian in age.

Anderson (1937; 1938a; 1938c; 1941b) in a series of papers and talks published only as abstracts expressed somewhat varying concepts of the stratigraphy and faunal succession of the California Cretaceous. A two-fold division of the Lower Cretaceous "Shasta series" into Paskenta group below, and Horsetown group above was retained; a three-fold division of the Upper Cretaceous "Chico series", with a basal Pioneer group, a middle Panoche group, and an upper Moreno or Orestimba group was commonly proposed. In at least two papers (Anderson 1940; 1941a) a stage subdivision was proposed, but the stages were never formally defined.

Popenoe (1937) in describing a number of mollusks from the Cretaceous rocks of the Santa Ana Mountains proposed a tentative grouping of the strata involved into three formations and five members. This stratigraphic classification, together with a detailed description of the members, the fauna, and the faunal zones recognized, and a discussion of the Cretaceous rocks and faunas of the nearby Santa Monica Mountains and Simi Hills, was elaborated in two later papers (Popenoe, 1942; 1943a).

Nonuniform and various uses of the term "Chico" as a name for the Upper Cretaceous series in California, or for one of its subdivisions led J. A. Taff, G. D. Hanna, and C. M. Cross (1940) to examine the Cretaceous section exposed in the canyon of Big Chico Creek in Butte County. They described the section, collected large numbers of fossils from 12 localities ranging from near the base to near the top, and figured and discussed a number of the more prolific molluscan species. The age of the beds in terms of the standard European stage sequence was not determined, but the authors suggested indirectly the advisability of restricting the term "Chico" to rocks of the same age as those exposed in the type section.

In the decade from 1940 to 1950, interest in Cretaceous stratigraphy and classification increased markedly, in part reflecting the revival of interest of oil companies in the commercial possibilities of the Cretaceous formations. A symposium held as part of the program of the Pacific Section, American Association of Petroleum Geologists, in Los Angeles, October 1941, was devoted to problems of Cretaceous stratigraphy, correlation, and nomenclature. Some of the papers read at the symposium and subsequently published include the following:

J. M. Kirby (1943) described six Upper Cretaceous formations of widespread development in the southern Sacramento Valley and named these in ascending order Venado, Yolo, Sites, Funks, Guinda, and Forbes. He designated type localities for each formation and described the lithology, distribution, and thickness of each. A tentative correlation was suggested with Cretaceous beds in some other California regions.

A. S. Huey (1948, p. 23–33) described the Cretaceous stratigraphy of the Tesla quadrangle on the west side of the San Joaquin valley and proposed the name "Moreno Grande" for beds which in the northern part of the Diablo Range are essentially equivalent to the Moreno formation of Anderson and Pack, but which, farther south near Coalinga, include beds commonly mapped as Moreno plus underlying strata down to the base of the so-called "Brown Mountain sandstone."

N. L. Taliaferro (1944) described the Cretaceous sequence in the Santa Lucia Range, stating that there the Lower Cretaceous Marmolejo formation of "Shasta" age lies unconformably or disconformably on "Franciscan" Knoxville beds and underlies unconformably the "early Upper Cretaceous?" Jack Creek formation, which in turn underlies unconformably the Asuncion formation of late Late Cretaceous age.

Popenoe (1943b) described a sequence of Upper Cretaceous members cropping out at the north end and east side of the Sacramento valley near Redding, defined six stratigraphic units, correlated the three lower with the Turonian and the three upper with the lower Senonian. Comparisons with some other Cretaceous sections in California were offered.

O. P. Jenkins (1943) presented a succinct historical review of published work to that date on the California Cretaceous and discussed the significance of current opinions.

Other papers of the decade include Taliaferro's (1943a) discussion of the geological history of the central Coast Ranges of California. Taliaferro pointed out that the Cretaceous formations recognized in the Santa Lucia Range near the Pacific Coast are separated by unconformities representing considerable periods of nondeposition and/or erosion, but that these unconformities appear to die out eastward toward the Diablo Range along the western border of the San Joaquin valley. A three-fold stratigraphic division of the Cretaceous beds of this general region was set up. The basal division, the Shasta group, was defined to include all beds from Infra-Valanginian to Aptian, inclusive; the middle Pacheco group included strata of ages from Albian through Turonian; the upper Asuncion group included all Senonian-Maestrichtian strata. The divisions are hence time-stratigraphic and not lithologic in character. This classification may well be valid in the Santa Lucia Range, but its validity in application to the Cretaceous of the Diablo Range farther east was questioned by Huey (1948, p. 29–30), and any evidence that the two upper divisions could be recognized structurally in the Sacramento Valley was strongly discounted by Kirby (1943, p. 304).

Goudkoff (1945) studied the Cretaceous

foraminiferal sequence found in well samples collected at many different localities and zones chiefly in the Sacramento valley. He subdivided the sections studied into 7 stages and 12 zones; the zones were designated by letter symbols and characterized by distinctive foraminiferal assemblages. He put forward a general correlation chart of the Cretaceous beds of California, which included a tentative correlation with the American Gulf Coast and the European Cretaceous. His zonation has been widely used. Some of its details need restudy, however, as there is some suggestion that the zones are determined in part by facies changes rather than by time changes.

By 1950 study of Cretaceous stratigraphy and paleontology in California had progressed to the stage where rock units such as formations and members had been discriminated and defined in a number of local sections, and where faunal zones, based upon detailed study of fairly comprehensive faunas, could be set up for a few sequences. The decade since 1950 has seen some furtherance of the more precise zonal and stratigraphic work begun in the late 1930's and early 1940's.

J. W. Durham and M. V. Kirk (1950) presented evidence for the probable Maestrichtian age of the *Coralliochama*-bearing beds at Punta Banda, Baja California, and from the Gualala formation in Mendocino County, California. However, O. L. Bandy (1951; 1952) on the basis of foraminiferal studies concluded that the *Coralliochama* beds were probably no younger than early or middle Campanian.

Max Payne (1951) described the stratigraphy of the Moreno formation at its type locality in Moreno Gulch in the Temblor Range on the west side of the San Joaquin Valley. He named and defined four new members of the Moreno formation and mapped these north from the type locality as far as they could be recognized in outcrop. He maintains that the "Garzas sand" as exposed in the vicinity of Garzas Creek lies stratigraphically below the top of the Panoche formation, rather than being equivalent to a high position in the Moreno formation, as maintained by F. M. Anderson and some others.

E. C. Allison (1955) described a molluscan fauna of more than 100 species collected from exposures of the Alisitos formation along the Pacific coast of Baja California south of Ensenada. The fauna, probably of Albian age, is peculiar in having its closest relationships with the Cretaceous of Texas, the Caribbean region, and of western Europe, and of having almost no close relationship with Albian faunas found elsewhere on the Pacific Coast.

Dallas L. Peck, R. W. Imlay, and W. P. Popenoe (1956) described the stratigraphic and faunal succession in the Cretaceous beds of Siskiyou County, in northern California, and named a new stratigraphic unit, the Hornbrook formation, which was subdivided into six members. A Turonian fauna was recovered from Member I at the base of the sequence and from the lower part of Member II; Members II and III were believed separated by a possible unconformity of undetermined magnitude; and a small but diagnostic assemblage of ammonites and *Inoceramus* from upper V and lower VI indicated a Campanian age for these members. The Cretaceous beds of the region have been mapped in detail more recently by David Jones (1959), who recognized three major stratigraphic units within the Hornbrook "formation" and considers the faunas from Member II to include lower Coniacian as well as Turonian elements.

Popenoe (1955, p. 23) showed that the Cretaceous beds of the Simi Hills in Los Angeles and Ventura counties are probably of late Campanian and early Maestrichtian age. The youngest beds of the sequence were considered slightly older than the base of the Moreno formation of the Diablo Range.

M. A. Murphy (1956) described the results of a careful stratigraphic, biostratigraphic, and faunal study of the classic Lower Cretaceous deposits of the Ono region, northern Sacramento valley. For the first time these Cretaceous rocks were mapped in detail, and the carefully collected faunas were tied precisely into their stratigraphic positions. Three important results of the study are: the lower Cretaceous beds of the region are included in the Rector and Ono formations; the beds containing the early Cretaceous faunas constitute the Horsetown stage; and nine local zones, eight of these within the Horsetown stage, are precisely defined in terms of the occurrence of diagnostic ammonite species and are mapped.

W. P. Irwin (1957) summarized the significance of recently discovered paleontological evidence for the age of the Franciscan group of the California Coast Ranges. The Franciscan was first described from exposures on the San Francisco peninsula by Lawson (1895), who later subdivided (1914) the group into five formations, which were considered to be of probable late Jurassic or early Cretaceous age. Later writers (*e.g.*, Reed, 1933: Taliaferro,

1943a; 1943b; etc.) have generally considered the group to be of late Jurassic age, mainly older than and subjacent to the Knoxville beds, and have assigned to it lithologically

F. M. Anderson (1958, posthumous) abandoned his previously proposed time-stratigraphic subdivisions of the Cretaceous and adopted the divisions of Shasta, Pacheco,

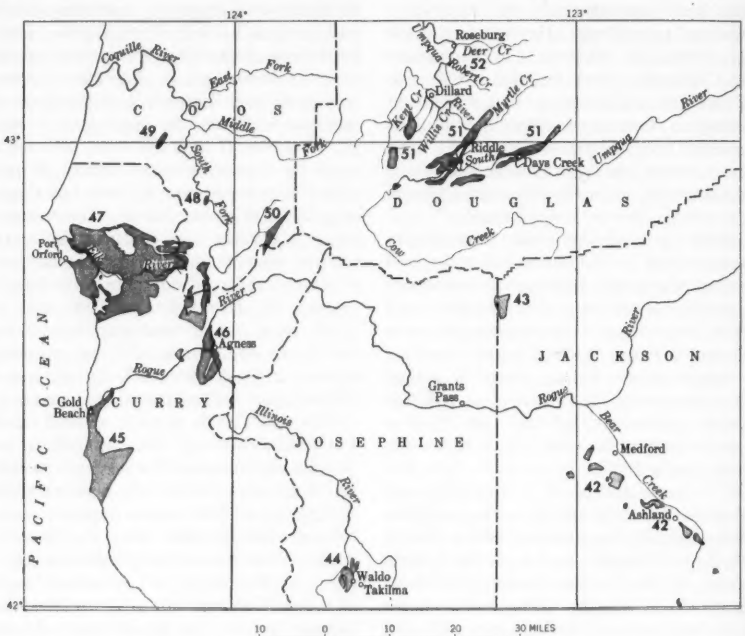

FIGURE 3.—INDEX MAP OF SOUTHWESTERN OREGON
Showing distribution of Cretaceous strata and positions of numbered columns 44 to 52 on Plate 1

similar rocks cropping out in the Coast Ranges from southwestern Oregon to southern California. The belt of Franciscan exposures is bordered on the east along much of its extent by a belt of upper Jurassic and lower Cretaceous strata commonly designated as the Knoxville, Paskenta, and Horsetown formations, together with some lower Upper Cretaceous.

Fossils recently collected from rocks generally considered Franciscan represent ages from Late Jurassic (Tithonian) to early Late Cretaceous (Cenomanian); at its type locality, the Franciscan has yielded only Cretaceous fossils. On this basis, Irwin interprets the Franciscan as comprising a sequence of eugeosynclinal deposits that accumulated contemporaneously with the Knoxville, "Paskenta", "Horsetown", and lower Upper Cretaceous foreland strata that crop out along the west borders of the San Joaquin and Sacramento valleys.

and Asuncion groups proposed by Taliaferro (1943a). The Asuncion group was divided into Lower Asuncion (Coniacian-Campanian) and Upper Asuncion (Maestrichtian) subgroups.

Tatsuro Matsumoto (1959a; 1959b; 1960) visited the United States in 1957 and 1958 and published the results of his careful and thorough study and review of the Late Cretaceous Californian ammonite faunas made available to him in American museums and collections. In these publications, Matsumoto offered a comprehensive treatment of the synonymy, stratigraphic position, and age significance of the species studied.

Much of the work reviewed above has been devoted to attempts to set up a provincial series and sub series classification of the Pacific Coast Cretaceous that would be of general application. These attempts have been somewhat less than successful. Viewed from the standpoint of present knowledge, this lack of

success stems from the fact that these classifications were erected without a sufficient foundation of detailed stratigraphic and biostratigraphic data; this condition still exists, at least as far as published information goes. Important areas of Cretaceous rocks, whose boundaries are fairly well known, have yet not been mapped, collected, described, and zoned in detail. The reasons for this are several.

Pacific Coast Cretaceous strata crop out in many more or less isolated areas. Some of these areas are extensive, and the exposed sections are thick; in others the sections are thin, and the outcrop area small. Structural complexity in places, difficulty of access, and abrupt and bewildering facies changes laterally and vertically are a few of the other factors that have held back progress in research; and not least is the lack of interest in the Cretaceous until recent years as a possible commercial source of oil and gas. Some very thick and comparatively complete sections are sparingly fossiliferous, and the detailed search for fossils necessary to zone such sequences faunally has not yet been made. Even those localities from which successions of well-preserved faunas are obtainable have been inadequately studied. The works of Packard (1916), Goudkoff (1945), Payne (1951), and Murphy (1956) are steps in the right direction, but more are needed. It is encouraging to know that others are under way.

Classifications proposed reflect some confusion in terminology. Generally used biostratigraphic terms such as "Paskenta beds" or "Horsetown beds" were originally coined for local occurrences and as such had a descriptive use. Their use has been extended at times to occurrences as widely separated geographically as Oregon and southern California, and to time spans encompassing two or more complete standard stages. When a biostratigraphic name is defined—*e.g.*, as including "all strata definitely referable to the Senonian," it becomes a synonym and should be treated as such.

Confusion in terminology has similarly resulted when a name—*e.g.*, Moreno or Asuncion—originally applied to a formation is transferred *in toto* to a biostratigraphic unit of stage rank or larger and is applied in areas to which the formation cannot be traced. In this process, the biostratigraphic unit almost inevitably comes to represent a different time span than does the formation from which it was spawned, and two or more different concepts of different magnitude are hence called by the same name.

One example of such terminological tangles is in the use of the word "Chico." It was originally used (Chico group, Gabb, 1869) for an inferred division of the lower Upper Cretaceous. It has since been used in a biostratigraphic sense as an upper Upper Cretaceous division, (Chico-Tejon series, White, 1885a, *et al.*,); in a biostratigraphic sense as including all the Pacific Coast Upper Cretaceous (Chico formation, Stanton 1895, etc.); as a group comprising the Upper Cretaceous, and composed of the Panoche and Moreno formations (Anderson and Pack, 1915); as a series name, essentially synonymous with Upper Cretaceous (Anderson, J. P. Smith, *et al.*); as a mappable formation of the Diablo Range lower Upper Cretaceous (Taff, 1935); and inferentially as a formation represented by the section exposed on Chico Creek (Taff, Hanna, and Cross, 1940). The term must then be accompanied in each usage by a definition, or its sense is not clear.

In the present state of knowledge a local or provincial series and/or subseries classification of the Pacific Coast Cretaceous appears impracticable. When increase of knowledge makes such a classification practicable it will no longer be necessary, for the Cretaceous formations can then be fitted into the standard stages of the Upper and Lower Cretaceous series of the Cretaceous system.

On the other hand, establishment of a provincial faunal zonation for the Pacific Coast Cretaceous is both practicable and desirable. This can be initiated by working out the detailed faunal succession in a number of local sections, in a manner similar to that employed by Murphy (1956) in northern California. The results from a number of local sections can eventually be synthesized to determine a faunal sequence of State-wide or Pacific Coast-wide scope. Such a zonation is practicable using at least three different groups—Foraminifera, Ammonoidea, and Gastropoda-Pelecypoda. Naturally the divisions of the zonations based on these different taxa would differ one from the other, but their results should be harmonious.

In conclusion an observation of Arkell (1933, p. 35, 36) regarding biostratigraphic procedure in the European Jurassic applies equally well to procedures in the Pacific Coast Cretaceous:

> "The tables of ammonite sequences which we have been considering, based as they are on careful field-work, represent definite and valuable additions to knowledge; for even if the restricted vertical distribution of ammonites observed in one locality be found to have changed in another, the mere discovery of this fact is knowledge gained. All such detailed field-investigations carry out the sound precept of Quenstedt, that we must get to know our successions minutely, as the very first step in

stratigraphical geology. It is absolutely essential that this work should be undertaken, for until the detailed knowledge of the rocks and faunas it provides is available for large areas, generalizations are impossible."

same locality. Little addition to the knowledge of the Cretaceous in Oregon appeared for more than 20 years, although reference to Gabb's and Blake's discoveries appeared in several

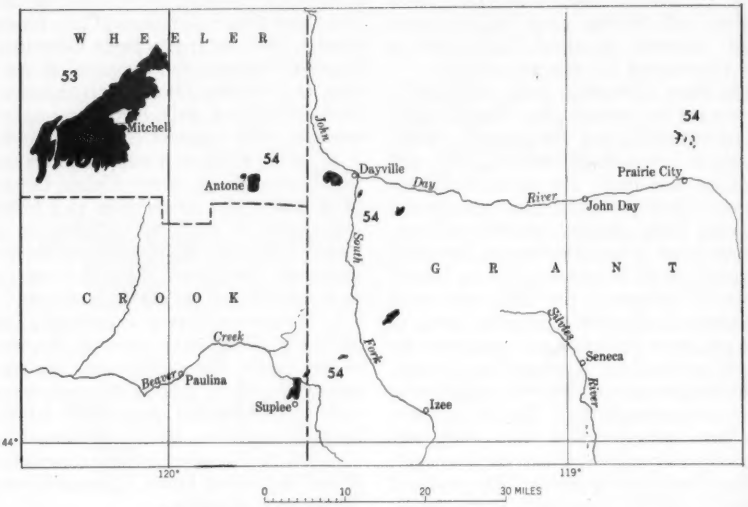

FIGURE 4.—INDEX MAP OF CENTRAL OREGON
Showing distribution of Cretaceous strata and positions of numbered columns 53 and 54 on Plate 1

Oregon and Washington

In general, investigations of Cretaceous stratigraphy and paleontology of Oregon and Washington are far less advanced than are those of California. Reasons for this are several-fold; the most important is perhaps that in these States Cretaceous rocks commonly have a much more limited areal extent, occur in relatively less accessible regions, and have been less intensively studied. Nevertheless considerable advances in knowledge have been made in recent years in both States, although much of the work is still unpublished.

Apparently the first published evidence for the presence of Cretaceous rocks in Oregon is cited by Gabb (1864, p. 220–236), who reported the occurrence of common Cretaceous species from Jacksonville in southern Oregon and in the Siskiyou Mountains. Professor Whitney (1867) announced the discovery by Gabb of Cretaceous fossils in central Oregon east of the Cascade Range, in the valley of Crooked River. Six months after Whitney's announcement, W. P. Blake (1867) published a note announcing the occurrence of Cretaceous fossils from the

papers. G. F. Becker (1891) announced the finding at several localities near Riddle, Oregon, of *Aucella crassicollis*. In the decade following, the known geographic extent of the *Aucella*-bearing beds was greatly increased through the work of J. S. Diller (1898; 1901; 1903), who gave the first detailed account of the stratigraphic and areal relations of the western Oregon Cretaceous in the Roseburg (1898), Coos Bay (1901), and Port Orford (1903) folios of the U. S. Geological Survey, and also defined and named the Myrtle formation.

In three later papers concluding his contributions to the Cretaceous stratigraphy of Oregon, Diller discussed the general features of the Jurassic–Cretaceous stratigraphic relationships (1907), the occurrence and significance of the fossil flora (1908), and the distribution of the Cretaceous in the Riddle quadrangle (Diller and Kay, 1924). Rather peculiarly, Diller and Kay borrowed the terms Knoxville and Horsetown from California and did not mention the "Myrtle formation" defined by Diller (1898) some years before, although the Cretaceous beds in Myrtle Creek valley, the type locality, extend into the Riddle quadrangle. In accord-

ance with the interpretations current in his day, Diller placed in the Cretaceous the beds bearing *Buchia* (*Aucella*) *piochii* (Gabb), now considered to be Jurassic.

since 1945, U. S. Geological Survey parties working in southwest Oregon under the direction of Francis Wells have published a number of quadrangle maps and a general geologic map

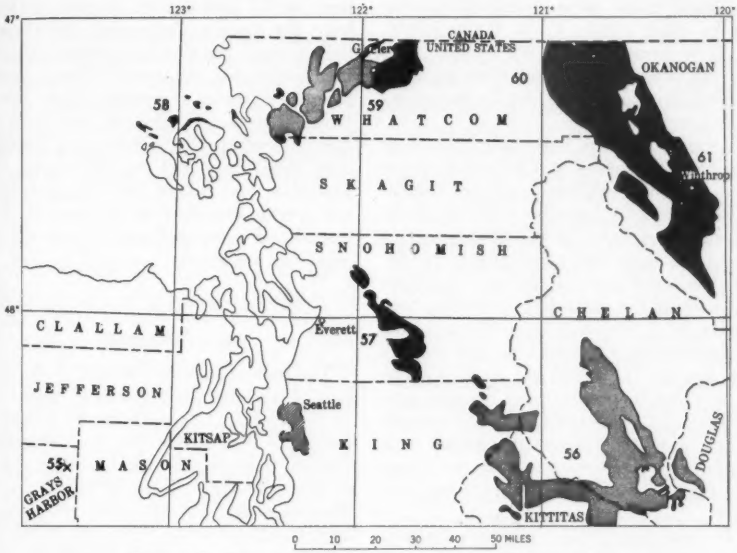

FIGURE 5.—INDEX MAP OF NORTHWESTERN WASHINGTON

Showing distribution of Cretaceous strata and positions of numbered columns 55 to 61 on Plate 1. Solid black—fossiliferous Cretaceous strata. Pattern—strata that have furnished Paleocene plants but possibly include nonmarine Upper Cretaceous. Other areas of Cretaceous rocks probably exist in northwest Washington.

F. M. Anderson (1895) described the occurrence and fauna of the Cretaceous near Phoenix, Oregon, amplifying this in 1902 with a more extended discussion of the inferred relations of the Phoenix fauna to that of the Cretaceous of California. J. C. Merriam (1901), in a discussion of the geology of the John Day basin, central Oregon, described briefly the occurrence of marine Cretaceous south of the basin and included two lists of Cretaceous fossils identified by T. W. Stanton, together with a discussion by Stanton of the probable age and significance of the faunas.

E. L. Packard (1928; 1939) added detail to the published knowledge of the Cretaceous of central Oregon and discussed the age span of the formations cropping out there. F. M. Anderson (1938b; 1958) discussed in general fashion some features of the age and faunas of Cretaceous occurrences in the State, but added little as to detailed stratigraphy of the rocks. Finally, in which the distribution of the Cretaceous of this region is accurately shown.

To sum up, although the areal exposures of Cretaceous rocks in Oregon have been fairly accurately determined, very little information is available in print on either stratigraphic or paleontologic detail. Although the presence of Cretaceous in the State has been known for nearly 100 years, no careful comprehensive faunal studies have been published, no accurately determined sections have been described with positions of the faunas noted, and only one Cretaceous formation has been formally described and named. A number of unpublished detailed studies that have been made within the last few years are nearing publication, however, and other studies are projected. It thus seems probable that the next decade will see a great deal added to our knowledge of Cretaceous formations and faunas of Oregon.

The first record of occurrence of Cretaceous

rocks in Washington is in a short paper by F. B. Meek (1861), who described eight new Cretaceous species from Vancouver Island and noted that two of these occurred also at Sucia Island in the San Juan group. Additions to the Sucia Island fauna were described in later papers by Meek (1876), C. A. White (1889), and J. F. Whiteaves (1879; 1903), and perhaps one or two other workers, but these accounts and descriptions include no details concerning the stratigraphy.

I. C. Russell (1900, p. 114) applied the name Similkameen formation to Cretaceous strata exposed along the headwaters of the Similkameen River, near the Canadian boundary about 70 miles north of Lake Chelan. This formation of sandstone, shale, and conglomerate yielded at one level specimens of the fern *Aspidium* and at another the gastropod *Acteonella*, both indicative of Cretaceous age, although the determinations made at that time gave no more precise age. G. O. Smith and F. C. Calkins (1904) working in approximately the same area pointed out that the extent of the Cretaceous beds here is much greater than Russell indicated and suggested the name Pasayten formation in place of Similkameen, which was preoccupied.

R. D. McLellan (1927) published the first detailed account of Cretaceous sections in Washington in his study of the geology of the San Juan Islands. He referred to the Spieden formation beds carrying the *Buchia crassicollis* fauna and cropping out on Spieden Island and on a few neighboring islands. On other islands along the northern border of the San Juan group, McLellan found a thick sequence of Upper Cretaceous beds which he correlated with those of the Nanaimo group of Vancouver Island. Notable highly fossiliferous exposures of the Nanaimo group are found on Waldron Island and particularly on Sucia Island, and from these localities have been collected almost all the specimens of species cited from this region by Meek, C. A. White, J. F. Whiteaves, and J. L. Usher (1952).

J. D. Barksdale (1948) described a section of very thick dark clastic rocks, principally black siltstone and graywacke with pebble conglomerate, cropping out in the Methow quadrangle along the Canadian boundary. He named this sequence the Virginian Ridge formation and, on the basis of poorly preserved fossils at the top of the basal conglomerate, dated it as Middle? Cretaceous. Conformably above the Virginian Ridge formation he identified the Winthrop sandstone, originally defined by Russell (1900), which carries a meager flora sufficient to indicate probable Late Cretaceous age.

To sum up, it seems probable that the Cretaceous stratigraphic units of Washington have been named and defined in more detail than have the Oregon Cretaceous formations. Although much remains to be done in describing the Washington faunas and floras, they also have been treated at greater length than have those of Oregon. Particularly, the fauna of the Nanaimo group of the San Juan Islands has been listed in detail by Whiteaves, Usher, McLellan, and others, but the nomenclature and specific identification of many of the gastropod and pelecypod species included in the fossil lists are greatly in need of review.

Correlations with European Stages

Berriasian

The Berriasian is represented in the western part of Washington by species of *Buchia* similar to *B. volgensis* (Lahusen) and *B. okensis* (Pavlow). (*See* Annotation 63). In California and Oregon, however, there are no certain records of any ammonite genera or *Buchia* species of Berriasian age. An ammonite from the Ono area, California, which Anderson (1938b, p. 160, 161, Table 2 opposite p. 44) assigned to *Spiliceras* of late Tithonian to Berriasian age, actually belongs to the genus *Hoplocrioceras* of late Hauterivian to Barremian age. The Berriasian species *Buchia okensis* (Pavlow) was reported by Anderson (1945, p. 940, 942) from the uppermost part of the Knoxville formation, but he did not publish any illustration. One specimen that was assigned to that species by Pavlow (1907, Pl. 1, figs. 10a–c) is reported to be from California. This report, as well as Anderson's, may be in error, as Imlay has not been able to find any representative of *B. okensis* (Pavlow) in the collections of the U. S. Geological Survey, of the California Academy of Sciences, or of Leland Stanford Junior University.

Other faunal evidence suggesting that the Berriasian may be missing in California and Oregon is the presence of the Valanginian species *Buchia crassicollis* (Keyserling) in the basal beds of the Cretaceous in those States and the absence of the species *Buchia sublaevis* (Keyserling) which in Alaska occurs directly below *B. crassicollis* Keyserling (Imlay, 1959, p. 161, 165) in beds of probable Valanginian age. Furthermore, in northern California the lower third to fourth of the beds characterized

by *Buchia crassicollis* (Keyserling) contain ammonites that are probably not older than Valanginian.

Proof of a hiatus representing Berriasian time has not been found, although in both Oregon and California the base of the beds containing *Buchia crassicollis* (Keyserling) is marked at many places by a massive sandstone or conglomerate that rests on Upper Jurassic beds. The association of such a sandstone, or conglomerate, with the first appearance of *Buchia crassicollis* (Keyserling) of Valanginian age suggests that the Berriasian is missing but does not prove it.

Valanginian

Beds of Valanginian age occur in northwestern Washington from Spieden Island in the San Juan group to eastern Whatcom County, in southwestern Oregon in Douglas, Josephine, Coos, and Curry counties, and in the Coast Ranges of California from Santa Barbara County on the south to the central part of Trinity County on the north. Their presence is generally easily determined by an abundance of *Buchia crassicollis* (Keyserling) which species in the Boreal region is characteristic of the Valanginian and reached its climax in middle to late Valanginian time.

These particular *Buchia*-bearing beds on the Pacific Coast have likewise been dated by means of ammonites studied by Imlay (Imlay *et al.* 1959, p. 2784), who has established the existence of an ammonite succession from top to bottom as follows:

Olcostephanus n. sp. aff. *O. jeannoti* (D'Orbigny)
Homolsomites mutabilis (Stanton)
Sarasinella hyatti (Stanton)
Kilianella crassiplicata (Stanton)

Kilianella crassiplicata (Stanton) and *Thurmanniceras californicum* (Stanton) (USGS Mes. locs. 1001, 1095, 5339) have been found only in the lower third to fourth of the beds containing *Buchia crassicollis* (Keyserling) in Tehama County, California. Their stratigraphic position is 700–1000 feet below the beds containing *Homolsomites mutabilis* (Stanton). Their age is considered middle Valanginian, although both genera range from late Berriasian to early Hauterivian. This age assignment is based on the close resemblance of *Kilianella crassiplicata* (Stanton) to *K. roubaudi* (D'orbigny) (Sayn, 1907, p. 47, Pl. 6, figs. 9, 10 a, b) from the middle Valanginian of France; on the resemblance of the inner whorls of *Thurmanniceras californicum* (Stanton) to *T. pertransiens* (Sayn) (1907, Pl. 5, figs. 5, 7) from the middle Valanginian of France; on the resemblance of the largest whorls of *T. californicum* (Stanton) to the large whorls of *T. novihispanicum* Imlay (1937, Pl. 78, fig. 8; Pl. 79, fig. 6) from the middle Valanginian of Mexico; and on the fact that *Thurmanniceras* attained its greatest development in the middle Valanginian and *Kilianella* in the middle and upper Valanginian.

Sarasinella hyatti (Stanton) has been found at six places in southwestern Oregon and has not been found in California. It has not been found in the *Homolsomites mutabilis* beds and differs from any of the species of *Sarasinella* found in those beds. It has been found about 500 feet lower stratigraphically than *Homolsomites mutabilis* (Stanton) on the South Fork of the Elk River in Curry County, Oregon. Elsewhere the relative stratigraphic positions of these species have not been ascertained. The age of *Sarasinella hyatti* (Stanton) is middle Valanginian on the basis of stratigraphic position and on the fact that the genus was uncommon before the middle Valanginian. As *Sarasinella hyatti* (Stanton) and *Kilianella crassiplicata* (Stanton) were not obtained in the same sequence of beds, there is no assurance that one species is younger than the other.

The beds characterized by *Homolsomites mutabilis* Stanton likewise contain the ammonites *Polyptychites trichotomus* (Stanton), *Neocraspedites* n. sp., *Thurmanniceras jenkinsi* (Anderson), *T. stippi* (Anderson), *Sarasinella angulata* (Stanton), *Bochianites paskentaensis* Anderson, and *Acanthodiscus* aff. *A. subradiatus* Uhlig. These date the beds readily as middle to late Valanginian because *Sarasinella* and *Polyptychites* are not known above the Valanginian, and *Acanthodiscus* and *Neocraspedites* are not known below the middle Valanginian. The association of *Neocraspedites*, *Acanthodiscus*, and *Crioceratites* favors a late rather than a middle Valanginian age because *Neocraspedites* reached its climax in the late Valanginian, *Acanthodiscus* in the early Hauterivian, and *Crioceratites* during the Hauterivian and Barremian. Comparisons of species of these genera with foreign species likewise favor a late Valanginian age. However, the species of *Polyptychites*, *Thurmanniceras*, and *Sarasinella* are more like foreign species of middle Valanginian than of late Valanginian age. Considering both faunal evidence and stratigraphic position above beds containing middle Valanginian ammonites, the *Homolsomites mutabilis* beds are herein assigned an early late Valanginian age.

The beds characterized by *Olcostephanus* n. sp. aff. *O. jeannoti* (D'Orbigny) are of late Valanginian age because they directly underlie beds of early Hauterivian age, contain the Valanginian *Buchia crassicollis* (Keyserling), and the particular species of *Olcostephanus* present has certain features found in species of late Valanginian and early Hauterivian ages. These features include densely spaced ribbing and absence of umbilical tubercles on the middle and outer whorls.

Hauterivian

Beds of Hauterivian age in California have been identified on the Wilcox Ranch in western Tehama County, near Ono in western Shasta County, and near the Clements Ranch on Redding Creek in the central part of Trinity County. In Oregon the Hauterivian has been identified at many places in Douglas, Coos, Curry, and Josephine counties. These beds have been dated by means of ammonites studied by Imlay (Imlay *et al.*, 1959) who has established a provisional ammonite succession from top to bottom as follows:

Hertleinites aguila (Anderson)
Simbirskites n. sp. aff. *S. elatus* (Trautschold)
Wellsia packardi (Anderson)
Wellsia oregonensis (Anderson)

Wellsia oregonensis (Anderson) has been found only in southwestern Oregon where it occurs above beds containing *Buchia crassicollis* (Keyserling). Its relative stratigraphic position is shown by exposures on the South Umpqua River near Days Creek where it was collected from 58 to 243 feet above the top of the *Buchia*-bearing beds. It is associated with a fairly large fauna of mollusks and crustaceans. Some of the other ammonites include *Phylloceras trinitense* Anderson, *P. umpquanum* Anderson, *Lytoceras aulaeum* Anderson, *Costidiscus* sp., *Hannaites riddlensis* (Anderson), and *Crioceratites latum* (Gabb). Some of the associated pelecypods include *Periplomya trinitensis* Anderson, *P. riddingensis* Anderson, *Pleuromya papyracea* Gabb, *Trigonia kayana* Anderson, and *Entolium operculiformis* (Gabb). None of these species has been found in the underlying beds containing *Buchia crassicollis* (Keyserling), but many of the species range up into beds of middle Hauterivian age.

Wellsia packardi (Anderson) has been found only in southwestern Oregon near Days Creek and Riddle in Douglas County. It is associated with the same assemblage of mollusks and crustaceans as *W. oregonensis* (Anderson). The fact that some of the Geological Survey collections, made near Riddle between 1890 and 1900, contain both *W. packardi* and *W. oregonensis* might be construed as evidence that those species are likewise naturally associated. The collections were not made stratigraphically, however. Also, the specimens of *W. packardi* are browner and generally more crushed than are those of *W. oregonensis* as though they were obtained from different beds. The local relative stratigraphic position of the two species was determined during 1954 by collecting along the South Umpqua River near Days Creek where *W. packardi* was obtained above the range of *W. oregonensis* and from 253 to 413 feet above the top of the beds containing *Buchia crassicollis* (Keyserling). Whether the species in question maintain the same stratigraphic relationships elsewhere must await future collecting.

The beds containing *Wellsia oregonensis* (Anderson) and *W. packardi* Anderson are of Hauterivian rather than of Valanginian age because they contain the distinctive Hauterivian ammonite *Spitidiscus* and a fair abundance of *Crioceratites* which is rare below the Hauterivian. They are assigned an early Hauterivian age because they overlie beds of late Valanginian age and underlie beds containing the ammonites *Simbirskites* and *Hollisites*.

Species of *Simbirskites* similar to *S. elatus* (Trautschold) and *S. progrediens* Lahusen have been found in Douglas, Coos, and Curry counties in southwestern Oregon at a stratigraphic position a little above the beds containing *Wellsia packardi* (Anderson). This has been determined only near the town of Riddle where *Simbirskites* and a new genus *Hollisites* was obtained from a sandstone bed at the west end of the bridge across Cow Creek. Associated with these ammonites near Agness in Curry County and along Foggy Creek road in Coos County are others that range upward from early Hauterivian beds. These include *Phylloceras trinitense* Anderson, *P. umpquanum* Anderson, *Hannaites riddlensis* (Anderson), *Lytoceras aulaeum* Anderson, and *Spitidiscus* sp. Also, associated are others that are similar to, or identical with, species that in California occur in beds of probable late Hauterivian age characterized by *Simbirskites broadi* Anderson and *Hertleinites aquila* (Anderson). These species include *Acrioceras voyanum* Anderson, *Hoplocrioceras* cf. *H. remondi* (Gabb), and a new species of *Hollisites*. Associated pelecypods include *Pleuromya papyracea* (Gabb), *Trigonia*

kayana Anderson, *Trigonia* cf. *T. leana* Gabb, and a new species of *Inoceramus*.

The beds in Oregon that contain *Simbirskites* cf. *S. elatus* (Trautschold) and the other ammonites listed above are considered middle to early late Hauterivian because of the presence of *Simbirskites* and because the new genus *Hollisites* greatly resembles *Speetoniceras* from the Hauterivian of Europe. The *Simbirskites* beds in Oregon are not correlated with the beds containing *Simbirskites* in Shasta County, California (Anderson, 1938b, p. 47–49) because the species of *Simbirskites* are different, few ammonite species occur in common, and the *Simbirskites* beds in Oregon include ammonite species that range upward from older Hauterivian beds in Oregon, but are not known from California. Because of these faunal differences the *Simbirskites* beds in Oregon are considered older than the beds containing *Simbirskites* in California and are correlated with the lower part of the range of *Simbirskites* in Europe.

Simbirskites broadi Anderson, *Acrioceras hamlini* (Anderson), and many associated ammonites were described by Anderson (1938b, Table 2, p. 47, 48) on the basis of collections (CAS locs. 113, 1665) made 3–6 miles southwest of Ono, Shasta County, California, and were assigned to his Hamlin-Broad zone. His statements (1938b, p. 47, 111, 122, 147, 154, 208) indicate that the fossils were collected 450–600 feet below a conglomerate that he considered marked the base of the Horsetown group. This particular conglomerate was later defined by Murphy (1956, p. 2108, 2111) as the Roaring River tongue of the Ono formation.

The ammonites associated with *Simbirskites broadi* Anderson were assigned by him to many different genera whose age ranges elsewhere in the world are Berriasian to Hauterivian. Imlay has studied these ammonites and assigns them to *Phylloceras*, *Lytoceras*, *Crioceratites*, *Acrioceras*, *Hoplocrioceras*, *Pseudothurmannia*?, and *Simbirskites*. These genera are perfectly normal for beds of Hauterivian age, and the association of the last three genera indicate that the beds are of middle or late Hauterivian age.

The status of the Hamlin-Broad zone of Anderson is in question as a result of recent field studies by Michael Murphy in the Ono area, California. In particular, on Eagle Creek near Ono he found *Simbirskites broadi* Anderson associated with *Hertleinites aguila* (Anderson) about 240 feet above the base of his Ono formation and 215 feet above the lowest occurrence of *H. aguila*. Of course, this occurrence does not prove that the specimens of *Simbirskites* collected by Anderson were from the *Hertleinites aguila* zone. It may simply mean that the genus ranges into that zone. Murphy considers, however, that Anderson's collections, made over a stratigraphic interval of 150 feet, are probably in part from the zone of *Hertleinites aguila* and in part from an older zone.

Beds containing *Hertleinites aguila* (Anderson) or certain associated mollusks have been identified near Ono in western Shasta County, California, on the Wilcox Ranch in the western part of Tehama County, California, and 4 miles south of Cave Junction, Josephine County, Oregon. These beds have furnished a large assemblage of ammonites, belemnites, gastropods, and pelecypods which have been listed by Anderson (1938b, p. 64, 114, 116, 121, 139, 146, 200, 201, 202, 227) and Murphy (1956, p. 2113). Some of the most useful for purposes of dating the beds are as follows:

Hertleinites aguila (Anderson) (common)
Simbirskites broadi Anderson (rare)
Crioceratites latum (Gabb)
Shasticrioceras sp. (rare)
Hoplocrioceras remondi (Gabb)
H. onoense Anderson
Ancyloceras? sp. (rare)
Lytoceras aulaeum Anderson
Lytoceras cf. *L. traski* Anderson
Phylloceras occidentale Anderson
Inoceramus ovatoides Anderson (common)

For correlation with the European stages only the ammonites *Simbirskites*, *Hoplocrioceras*, *Crioceratites*, and *Hertleinites* have much significance. *Simbirskites* is a characteristic Hauterivian genus, although there is a record of the genus in the late Valanginian of Argentina (Leanza, 1955 [1957]) and questionable records from the early Barremian. *Hoplocrioceras* is reported to range from the middle Hauterivian into the Barremian, but most of the records of the genus are from beds of late Hauterivian age. *Crioceratites* ranges from the late Valanginian through the Barremian, but most of its records are from the Hauterivian. *Hertleinites* has not been recorded outside California, but its resemblance to the late Hauterivian genus *Craspedodiscus* may indicate a similar age. The evidence from these ammonites favors, therefore, a Hauterivian rather than a Barremian age and a late Hauterivian rather than an earlier age. This is supported by the stratigraphic position of the *Hertleinites aguila* beds below beds containing *Pulchellia* and *Ancyloceras* in the *Shasticrioceras poniente* zone. The evidence is not positive, however.

Barremian

The *Shasticrioceras poniente* zone (Murphy, 1956, p. 2113) has been identified by its index species (1) near Ono, Shasta County, California, (2) about 5 miles south of Cave Junction, Josephine County, Oregon, (3) about 4½ miles north of Winthrop, Okanogan County, Washington, and (4) in nearby parts of British Columbia. This species is commonly associated with *Inoceramus ovatoides* Anderson (equals *I. colonicus* Anderson), which also occurs in the underlying *Hertleinites aguila* zone. The Barremian age of the *Shasticrioceras poniente* zone is based on the presence of the ammonite *Pulchellia* in its lower part and of abundant *Ancyloceras* in its upper part. Elsewhere in the world *Pulchellia* ranges through the Barremian but is most common in the lower part of the stage, and *Ancyloceras* ranges from upper Barremian into lower Aptian. So the succession in California is normal. *Shasticrioceras* itself is known elsewhere only in Japan (Matsumoto *et al.*, 1953, p. 75, 76, 123) associated with other ammonites of Barremian age.

Aptian

The Aptian stage is represented by the *Gabbioceras wintunium*, *Acanthohoplites gardneri*, and *A. reesidei* zones (Murphy 1956, p. 2112–2116) and has been identified on the Pacific Coast only in western Shasta County, California. From the *G. wintunium* zone Murphy records *Phylloceras onoense* Stanton, *Gabbioceras wintunium* Anderson, *Tropaeum percostatum* (Gabb), and *Lytoceras traski* Anderson. He also includes *Deshayesites? seniloides* (Anderson), *Melchiorites indigenes* Anderson, and *M. shastensis* (Anderson).

Murphy divides the *Gabbioceras wintunium* zone into three subzones and lists characteristic fossils from each. The lower subzone has not furnished any diagnostic ammonites. The middle subzone is characterized by an undescribed species of *Gabbioceras*, but includes also *Australiceras argus* Anderson, *Deshayesites? shoupei* (Anderson), *Parahoplites dallasi* Anderson, and *Shastoceras shastense* Anderson. The upper subzone is characterized by *Gabbioceras angulatum* Anderson, *Lytoceras batesi* Trask, *Phylloceras aldersoni* Anderson, and *Columbiceras cerrosensis* (Anderson), but includes also *Hulenites reesidei* (Anderson) and *Hamulina aldersoni* Anderson. *Hamiticeras aequicostatum* (Gabb) occurs in the middle and upper parts of the upper subzone.

This ammonite assemblage contrasts markedly with that in the underlying *Shasticrioceras poniente* zone (Murphy, 1956, Fig. 6 p. 2114). Except for *Phylloceras*, *Lytoceras*, and *Melchiorites* all ammonite genera are different. Furthermore, the only ammonite species in common is *Melchiorites indigenes* Anderson which was found in the *S. poniente* zone at its top. Perhaps these differences are related to a scarcity of ammonites in the lower subzone of the *Gabbioceras wintunium* zone.

An Aptian age for the *Gabbioceras wintunium* zone is proved by the genera present. Elsewhere in the world *Tropaeum*, *Colombiceras*, and *Parahoplites* indicate the upper Aptian, *Deshayesites* ranges through the Aptian but is uncommon in the upper Aptian, *Hamiticeras* ranges from the upper Barremian into the Aptian, *Hamulina* is much more common in the Barremian, and *Gabbioceras* and *Australiceras* are not known below the Aptian. If these genera have the same ranges in California, then the middle and upper subzones of the *G. wintunium* zone should correspond to the middle and upper parts of the Aptian stage. The presence of *Parahoplites* in the middle subzone suggests that it is not as old as the lowest Aptian zone of *Deshaysites deshayesi.*

The zones of *Acanthohoplites gardneri* and *A. reesidei* (Murphy, 1956, p. 2117) have been recognized only near Ono in western Shasta County, California. They show close faunal relationships with each other and with the underlying *Gabbioceras wintunium* zone, but not with the overlying zone of *Leconteites leconteii*. *Hulenites reesidei* (Anderson) ranges from near the top of the *Gabbioceras wintunium* zone into the *A. reesidei* zone but is common only in the *A. gardneri* zone (Murphy, 1956, p. 2114–2115). *Ptychoceras laeve* Gabb ranges from the middle part of the *Gabbioceras wintunium* zone into the *Leconteites leconteii* zone. *Gabbioceras angulatum* Anderson ranges into the *A. gardneri* zone from the upper part of the *Gabbioceras wintunium* zone.

The ages of the zones of *Acanthohoplites gardneri* and *A. reesidei* cannot be determined exactly by the genera. *Acanthohoplites* and *Ptychoceras* are known elsewhere from beds of late Aptian to early Albian age. *Gabbioceras* occurs in beds of late Aptian to early Cenomanian age. Most of the collections of *Hulenites reesidei* (Anderson) were obtained from the zones under consideration, but some occur in *Gabbioceras wintunium* zone which contains late Aptian ammonites.

The ages of *Acanthohoplites gardneri* and *A. reesidei* can be determined approximately by

their stratigraphic position above beds containing the late Aptian ammonites *Colombiceras* and *Parahoplites* and beneath beds containing the Albian ammonite *Douvilleiceras* which in Europe occurs as low as the upper part of the *Leymeriella tardefurcata* zone. On a stratigraphic basis, therefore, the zones in question must be latest Aptian or earliest Albian, or both. They appear to occupy the position of the European *Diadochoceras nodosocostatum* zone and the lower part of the *Leymeriella tardefurcata* zone.

Opinions differ as to whether the zone of *Diadochoceras nodosocostatum* is of latest Aptian or of earliest Albian age, and the matter probably will not be settled until much more paleontologic and stratigraphic work is done. In the meantime the writers propose to use the Aptian-Albian classification proposed by Wright (1957, *in* Arkell, Kummel, and Wright, p. L128), which differs slightly from that of L. F. Spath (1941, p. 668) or that of Muller and Schenck (1943). Under this classification the *Diadochoceras nodosocostatum* zone is considered Late Aptian.

Albian

The *Leconteites lecontei* zone (Murphy, 1956, p. 2118) contains an ammonite assemblage characterized by *Leconteites*, *Puzosigella*, and *Tetrahoplitoides*. These have not been recorded from other zones or from other continents, although similar genera occur in the lower Albian in other continents. Among the species present *Phylloceras californicum* (Anderson) and *Ptychoceras laeve* Gabb range up from the underlying zones. *Anagaudryceras aurarium* (Anderson) and *Douvilleceras* aff. *D. mammillatum* (Schlotheim) range into the overlying zone. The assemblage has been recorded (1) from near Ono in Shasta County, California; (2) Hospital Canyon in San Joaquin County, California; (3) Tesla quadrangle in Alameda County, California; (4) near Mitchell in Wheeler County, Oregon; (5) in the Queen Charlotte Islands, British Columbia; and (6) in the Chitina Valley in southern Alaska.

The zone of *Leconteites lecontei* is undoubtedly of early or middle Albian age because it contains the ammonite *Douvilleiceras* which in Europe ranges from the upper part of the *Leymeriella tardefurcata* zone into the middle part of the *Hoplites dentatus* zone. An early Albian age is favored, however, by the presence of such ammonites as *Ptychoceras* and *Silesites* which normally are early Albian or older, and because *Douvilliceras* occurs likewise in the next two overlying zones. Such a range for *Douvilleiceras* in California corresponds very well with the range of the genus in Europe. Among the other ammonites, *Leconteites* resembles *Subarcthoplites* and *Lemuroceras* of early Albian age, and *Tetrahoplitoides* resembles *Gastroplites* of middle Albian age.

The zone of *Beudanticeras* (*Brewericeras*) *hulenense* (Murphy, 1956, p. 2118) has been identified near Ono in Shasta County, California, and probably occurs farther south in Tehama and Glenn counties (Anderson, 1938b, p. 68, 190). Near Ono the zone contains (Murphy, 1956, p. 2114, 2115) *Beudanticeras* (*Brewericeras*) *hulenense* (Anderson), *Desmoceras merriami* Anderson, *Puzosia subquadrata* Anderson, *Gabbioceras gainesi* Anderson, *Anagaudryceras aurarium* (Anderson), *Tetragonites* cf. *T. timotheanum* (Pictet), *Douvilleiceras restitutum* Anderson, and *D.* aff. *D. mammillatum* Schlotheim. The last species was referred by Breistroffer (1947, p. 65) to *D. monile* var. *aequinodum* (Quenstedt). In addition to these Murphy reports the presence of *Hypacanthoplites* sp. Murphy indicates that *Douvilleiceras*, *Desmoceras*, and *Beudanticeras* (*Brewericeras*) are particularly common. The zone of *B. hulenense* because of the association of *Douvilleiceras* and *Hypacanthoplites* could be correlated with either the upper part of the *Leymeriella tardifurcata* zone or with the *Douvilleiceras mammillatum* zone of Europe. A correlation with the latter is suggested by an abundance of *Douvilleiceras* in the *B. hulense* zone and, also, by the presence of the genus in the underlying *Leconteites lecontei* zone, which may reasonably be correlated with the lowest occurrence of the genus in Europe.

The zone of *Oxytropidoceras packardi* (Murphy, 1956, p. 2114, 2115, 2119; Anderson, 1938b, p. 69; Murphy and Rodda, 1959) has been identified only near Ono and Horsetown, Shasta County, California. Besides *O. packardi* Anderson, the zone contains *Puzosia aldersona* Anderson, *P. subquadrata* Anderson, *P. hoffmani* (Gabb), *Beudanticeras* (*Brewericeras*) *haydeni* (Gabb), *Douvilleiceras restitutum* Anderson, and *Cleoniceras susukii* Murphy and Rodda. Of these ammonites, *Oxytropidoceras* is a characteristic middle Albian genus, and *Douvilleiceras* and *Cleoniceras* are not known in Europe above the middle part of the middle Albian.

The *Mortoniceras hulenanum* zone (Murphy, 1956, p. 2114, 2115, 2119; Anderson, 1938b, p. 69) in western Shasta County, California, has furnished *Mortoniceras hulenanum* (Anderson), *M. kiliani* (Lasswitz), *Beudanticeras* (*Brewericeras*) *haydeni* (Gabb), *Desmoceras* (*Pseudouhligella*) *vetus* Murphy and Rodda, *D.* (*P.*)

dawsoni (Whiteaves), *Pachydesmoceras colusaense* (Anderson), and *Anagaudryceras* cf. *A. sacya* (Forbes) (Matsumoto, 1960, p. 24). Of these genera, *Mortoniceras* is typical of the late Albian in many parts of the world.

Mortoniceras has likewise been found in California in western Tehama County (Reagan, 1924), on the west side of Logan Ridge in Colusa County, on the north side of Wartham Canyon in Fresno County, near Fruto in Glenn County, on Putah Creek in Solano County, and 9 miles northwest of New Idria in San Benito County. In Central Oregon the genus has been found near Mitchell in Wheeler County.

Associated with *Mortoniceras* on the west side of Logan Ridge are *Desmoceras* (*Pseudouhligella*) *dawsoni* Whiteaves, *Pachydesmoceras colusaense* (Anderson), *Hysteroceras varicosum* (Sowerby), *Idiohamites* sp., *Pseudohelicoceras petersoni* (Anderson), and *Beudanticeras* (*Brewericeras*) cf. *B. haydeni* (Gabb) (Matsumoto, 1960, p. 35). These fossils occur in reworked blocks in the "Antelope" shale which contains the Cenomanian ammonites, *Turrilites*, *Calycoceras* and *Euomphaloceras* according to David Jones (Fossil report dated January 19, 1959).

Cenomanian

In central and southwestern Oregon and along the west sides of the Sacramento and San Joaquin valleys beds of Cenomanian age have been identified by the ammonites *Turrilites*, *Desmoceras* (*Pseudouhligella*), *Mantelliceras*, *Marshallites*, *Stoliczkaia*, *Forbesiceras*, *Eogunnarites*, *Eucalycoceras*, *Calycoceras*, and *Acanthoceras*. In central Oregon *Turrilites oregonensis* Gabb (synonym of *T. costatus* Lamarck) associated with *Desmoceras* (*Pseudouhligella*) *japonicum* Yabe (identified by Matsumoto) has been found on the Andrew Bernard Ranch on Beaver Creek (USGS) Mes. locs. 26279, 26708) and on Battle Creek (USGS Mes. loc. 26375). In southwestern Oregon *Mantelliceras* occurs in the basal Cretaceous beds near Jacksonville (USGS Mes. locs. 26281). At Dark Hollow south of Medford *Desmoceras* (*Pseudouhligella*) was found with *Anagaudryceras* cf. *A. sacya* Forbes (USGS Mes. locs. 25220, 26280).

In California *Eucalycoceras*(?) *shastense* (Reagan) (1924, p. 179, Pl. 18, fig. 1) is recorded from Cottonwood Creek in Shasta County and from Willow Creek in Glenn County (LSJU coll.). *Stoliczkaia* has been found on Cottonwood Creek in Shasta County (UC coll.). *Turrilites costatus* Lamarck (identified by Matsumoto) occurs on Quinto Creek in Stanislaus County (CAS 27858) and in the Berkeley Hills (CAS 33729). *Puzosia weaveri* Anderson (1938, p. 189) was found with, or near, the holotype of *Mantelliceras lecontei* (Anderson) (1958b, p. 242) in the Fernandez Tunnel of the Santa Fe Railroad 3 miles east of Rodeo in Contra Costa County. *Mantelliceras* was found, also, on the north side of the Golden Gate (Hertlein, 1956). *Marshallites* aff. *M. olcostephenoides* Matsumoto (*see* Anderson, 1902, p. 101, Pl. 5, figs. 126, 127) was found in Cottonwood Creek in Shasta County. *Calycoceras* was found 1 mile east of the lower end of Huling Creek in Shasta County, in Curry Canyon southeast of Mount Diablo, and near Logan Ridge in Colusa County. *Forbesiceras* was found in the "lower Waltham shale member" of the Panoche formation in Wartham (Waltham) Canyon, Fresno County, associated with *Acanthoceras* and *Turrilites*. *Desmoceras* (*Pseudouhligella*) *japonicum* Yabe was obtained on Cottonwood Creek, Shasta County, and near Logan Ridge, Colusa County, *Acanthoceras turneri* White (not Sowerby) was found in Curry Canyon southeast of Mount Diablo.

Of these genera *Turrilites* and *Desmoceras* (*Pseudouhligella*) range from upper Albian to lower Turonian but are most common in the Cenomanian. *Acanthoceras* is typical of the upper Cenomanian, and *Mantelliceras* of the lower Cenomanian. *Stoliczkaia* ranges from the upper Albian into the early Cenomanian. *Marshallites* ranges through the Cenomanian into the lower Turonian. *Calycoceras* ranges through the Cenomanian into the lower Turonian. *Forbesiceras* has been found in the upper Cenomanian. Considering these ranges the occurrence of certain genera are not positive evidence of a Cenomanian age. Nevertheless none of these genera has been found in definite Turonian beds on the Pacific Coast.

Turonian

The early Turonian is characterized in California and Oregon by the ammonites *Kanabiceras septemseriatum* (Cragin), *Vascoceras shastensis* Anderson, and *Plesiovascoceras californicum* (Anderson) and by the pelecypod *Inoceramus labiatus* (Schlotheim). Of these *Kanabiceras septemseriatum* (Cragin) (equals *K. kanabense* (Stanton) has been found on Roaring River, Shasta County, associated with *Plesiovascoceras californicum* (Anderson), *Puzosia intermedia orientalis Matsumoto*, and *Mesopuzosia* (Matsumoto, 1960, p. 27). It occurs on Garzas Creek in the Pacheco Pass

quadrangle, Stanislaus County, associated with *Sciponoceras* Kossmati (Anderson) and *Inoceramus* cf. *I. labiatus* (Schlotheim) (Matsumoto, 1960, p. 51). Besides the occurrence in Shasta County *Plesiovascoceras californicum* (Anderson), or a similar species, has been found on the Fitch Ranch about 2 miles west of Phoenix, Jackson County, Oregon; from Hays Gulch near Gas Point in Shasta County, California (Anderson, 1931b, p. 123 Pl. 16, figs. 1, 2); from the Logan Ridge area, Colusa County, California (Matsumoto, 1960, p. 35); and in Wartham (Waltham), canyon on the west tributary of Oak Flat canyon (LSJU loc. 2956), Fresno County.

Among these ammonites the early Turonian is represented by *Vascoceras* and *Plesiovascoceras* and probably by *Kanabiceras*. *Kanabiceras septemseriatum* (Cragin) in the western interior has been found only in the zone of *Sciponoceras gracile* (Cobban and Reeside, 1952, p. 1017) which is either earliest Turonian or latest Cenomanian.

The middle to late Turonian is represented in California and Oregon by the ammonites *Romaniceras*, *Otoscaphites*, *Mesopuzosia*, *Parapuzosia*, *Tragodesmoceras*, *Coilopoceras*, *Collignoniceras*, *Scalarites*, *Hyphantoceras*, *Subprionocyclus*, and *Jimboiceras*. These have been found in California in the Santa Ana Mountains, along the west sides of the San Joaquin and Sacramento valleys, in the Redding district of Shasta County, and in the Hornbrook-Yreka area of Siskiyou County. In Oregon they have been found at many localities in Jackson County. These ammonites are associated commonly with such pelecypods as *Glycymeris pacificus* (Anderson), *Inoceramus hobetsensis* Nagao and Matsumoto, and *I. klamathensis* Anderson. *I. klamathensis* is identical with *I. teshioensis* Nagao and Matsumoto (identified by Tatsuro Matsumoto) from the Turonian of Japan, and both are synonyms of *I. perplexus* Whitfield.

Among these ammonites *Collignoniceras* is good evidence of a middle Turonian age, and *Subprionocyclus* of a middle to late Turonian age. Such genera as *Scalarities*, *Jimboiceras*, *Hyphantoceras*, *Otoscaphites*, and *Mesopuzosia* range higher. *Romaniceras* is not known above the Turonian. *Tragodesmoceras* ranges from the lower Turonian into the Coniacian but is rare above the Turonian and in the western interior is known only from the lower Turonian. In collections from the Fitch Ranch 3 miles west of Phoenix, Oregon, this genus is associated with *Subprionocyclus* (USGS Mes. locs. 703, 2264; CAS loc. 4685), but the fossils were obtained from rubble and need not have been obtained from the same beds. At other localities where *Tragodesmoceras* has been collected it is not associated with *Subprionocyclus*, and at Redding it occurs definitely below *Subprionocyclus* in association with *Inoceramus hobetsensis* Nagao and Matsumoto of middle Turonian age. The occurrences of some of the middle to late Turonian ammonites are as follows:

NAME	LOCALITIES
Scalarites ellipticum (Anderson)	49 Mine near Phoenix, Oregon
Otoscaphites spp.	(1) 49 Mine an Fitch Ranch near Phoenix, Oregon (2) Members II and III in Redding district, Shasta County, Calif. (3) Baker Canyon conglomerate member of Ladd formation in Santa Ana Mountains, Calif. (4) Near base of lower arkosic sandstone in Santa Monica Mountains
Mesopuzosia cf. *M. yubarense* (Jimbo)	Rancheria Gulch west of Henley in Siskiyou Company, Calif.
Coilopoceras hyatti Anderson	(1) 15 miles southwest of Beegum on Dry Creek road, Tehama County, Calif.
Romaniceras spp.	(1) Members II, III, and lower part of IV in Redding district, Calif. (2) Excavation for Monticello Dam at Putah Creek, Yolo County, Calif. in Venado formation of Kirby, (1943) (3) North Fork of Cottonwood Creek, Shasta County, Calif.
Jimboiceras planulatiforme (Jimbo) (identified by Tatsuro Matsumoto)	15.1 miles southwest of Beegum on Dry Creek Road, Tehama County, Calif.
Jimboiceras cf. *J. planulatiforme* (Jimbo)	Member II in Redding district, Shasta County, Calif.
Collignoniceras woollgari (Mantell) (equals *C. bakeri* Anderson)	(1) Near Phoenix, Jackson County, Ore.

NAME	LOCALITIES
	(2) North and Middle forks of Cottonwood Creek, Shasta County, Calif. (3) Horsetown area, Shasta County, Calif. (4) Dry Creek, Tehama County, Calif. (5) Quinto Creek in western Merced County, Calif.
Collignoniceras branneri (Anderson)	(1) Fitch Ranch near Phoenix, Jackson County, Ore.
Subprionocyclus spp.	(1) Near Phoenix, Jackson County, Ore. (2) Near Henley, Siskiyou County, Calif. (3) North and Middle forks of Cottonwood Creek, Shasta County, Calif. (4) Members II and III, Redding district, Shasta County, Calif. (5) Dry Creek, Tehama County, Calif. (6) Quinto Creek, western Merced County, Calif. (7) Pleasanton area near Arroyo del Valle, Alameda County, Calif. (8) Santa Ana Mountains, Orange County, Calif.
Tragodesmoceras ashlandicum (Anderson)	(1) Member 1, Redding district, Shasta County, Calif. (2) Hillside west of railroad 4 miles southeast of Ashland, Jackson County, Ore. (3) Fitch Ranch, 3 miles west of Phoenix, Jackson County, Ore.
Sciponoceras spp.	(1) Santa Ana Mountains, Orange County, Calif. (2) Quinto Creek, western Merced County, Calif. (3) Arroyo del Valle, Alameda County, Calif.
Hyphantoceras aff. *H. venustum* (Yabe)	Santa Ana Mountains, Orange County, Calif.
Scalarites spp.	Quinto Creek, western Merced County, Calif.

Coniacian

Beds of Coniacian age have been found at several places in California. In Siskiyou County *Kossmaticeras* cf. *K. pachystoma* (Kossmat) (equals *Nowakites klamathonis* Anderson according to Matsumoto, 1960, p. 3) and *Prionocycloceras crenulatum* (Anderson) (1902, p. 125, Pl. 1, fig. 125) were obtained south of Black Mountain in sec. 26, T. 46 N., R. 6 W.

In the Redding area, Shasta County, W. P. Popenoe collected ammonites of Coniacian age in the upper two-thirds of Member IV. One collection (CIT-1034) from near the middle of Member IV contains the typical Coniacian ammonites *Peroniceras shastense* Anderson and *Prionocycloceras(?)*. Other collections from Member IV contain *Hauericeras* sp., *Texanites* cf. *T. kawasakii* (Kawada), *Eupachydiscus* aff. *E. teshioensis* (Jimbo), *Baculites schencki* Matsumoto (common), *B. boulei* Collignon, *B. capensis* Woods, *Inoceramus* cf. *I. cordiformis* Sowerby, and *I.* aff. *I. naumanni* Yokoyama (Matsumoto, 1960, p. 9). These fossils in association indicate a Coniacian age. The genera *Eupachydiscus* and *Texanites* in particular are not older than later Coniacian.

On Chico Creek the Coniacian may be represented by the basal 700 feet of conglomeratic beds on the basis of the presence of *Baculites schencki* Matsumoto (1959a, p. 113–118). This species elsewhere in California occurs in beds of Coniacian to Santonian age and is particularly common in Member IV in the Redding area.

The characteristic Coniacian ammonite, *Peroniceras*, has been found also on Battle Creek, Tehama County (Gabb, 1864, p. 60, Pl. 10, fig. 4; 1869, p. 132, 133), in the Funks formation in the Rumsey Hills area, Yolo and Colusa counties, associated with *Prionocycloceras crenulatum* (Anderson) (Matsumoto, 1960, p. 33), and on Quinto Creek, Stanislaus County (Anderson, 1958, p. 260), a little above beds containing *Collignoniceras* and *Subprionocyclus*.

The presence of the Coniacian in the Panoche Hills is indicated according to Matsumoto (1960, p. 42) by *Baculites schencki* Matsumoto and *Inoceramus* cf. *I. uwajimensis* Yehara. It is possibly represented in the Ortigalita Peak quadrangle by *Baculites yokoyamai* Tokunaga and Shimizu and in the Santa Ana Mountains by *B. boulei* Collignon according to Matsumoto (1960, p. 45, 65).

Santonian

The presence of beds of Santonian age in the West Coast area has been demonstrated faunally at only a few places. There are no records of such genera as *Placenticeras* and *Parapuzosia* (*Parapuzosia*) that are common in the stage elsewhere. Such genera as *Eupachydiscus*, *Anapachydiscus*, *Hauericeras*, *Texanites*, and *Mesopuzosia* that might be of Santonian age are generally associated in California with other ammonites that are distinctly older or younger than Santonian.

The best-established occurrence of Santonian in California is on Chico Creek from about 700 to 1700 feet above the base of the Cretaceous sequence. These beds according to Tatsuro Matsumoto (1960, p. 17, 18) contain *Baculites capensis* Woods, a good Santonian marker, and *Inoceramus naumanni* Yokoyama, which in Japan ranges from the late Coniacian to the early Campanian. Other elements in the faunule that favor a Santonian age are *Hauericeras angustum* Yabe, *Hyphantoceras venustum* (Yabe), and *Inoceramus* cf. *I. undulatoplicatus* Roemer. The last two species indicate that the beds are not younger than Santonian.

In the Redding area the lower part of Member V is probably of early Santonian age. The highest part of Member V as well as the lower part of Member VI are of late Santonian age (Matsumoto, 1960, p. 12). A Santonian age for both members is indicated by *Inoceramus cordiformis* Sowerby and *Inoceramus naumanni* Yokoyama. A Santonian age for Member V is favored, also, by the presence of *Baculites capensis* Woods and *Bostrychoceras otsukai* (Yabe), although both species range from the upper Coniacian into the Santonian. A late Santonian age for the lower part of Member VI is indicated by the presence of *Inoceramus orientalis ambiguus* Nagao and Matsumoto, judging by the occurrence of that subspecies in Japan, and by the presence of *Pseudoschloenbachia*, which is not known below the upper Santonian. It is possible that the upper part of Member VI is of earliest Campanian age, but fossil evidence is lacking.

Elsewhere in California the Santonian has been identified by Matsumoto (1960, p. 43) in the Panoche Hills in Fresno and San Benito counties by the association of *Baculites capensis* Woods, *Anapachydiscus* sp., and *Inoceramus naumanni* Nagao and Matsumoto. He compares this faunule with that found on Chico Creek from 700 to 1700 feet above the base of the Cretaceous as measured by LouElla Saul.

Campanian

Beds of Campanian age containing a large molluscan fauna are widely distributed in California. In Oregon they occur along the coast in Curry County and are probably present in the valley of the Rogue River in Jackson County. In Washington the Campanian has been identified definitely only in the northern part of the San Juan Islands but may exist elsewhere in the northwestern part of the State. The incomplete ammonite succession, from top to bottom, appears to be as follows:

Hoplitoplacenticeras vancouverense (Meek)
Metaplacenticeras pacificum (Smith)
Patagiosites and *Anapachydiscus*
Submortoniceras chicoense (Gabb).

The beds containing *Submortoniceras* are known best from exposures on the east side of the Sacramento Valley on Chico Creek, Butte Creek, Pentz Ranch, and Mill Creek. On Chico Creek *Submortoniceras chicoense* (Trask) and *Baculites chicoensis* Trask characterize the upper half of the Chico formation except for the upper 400 feet. With these ammonites are associated many others (*see* lists in Matsumoto, 1960, p. 17–20) including in particular *Canadoceras newberryanum* (Meek), *C. yokoyamai* (Jimbo), *Pachydiscus buckhami* Usher, and *P. neevesi* Whiteaves. Matsumoto (1960, p. 18) notes that *C. yokoyamai* (Jimbo) is rather common in the lower part of the range of *Submortoniceras*, and *C. newberryanum* (Meek) has been found only in the upper third of the range of *Submortoniceras*.

On Pentz Ranch a collection (CAS 1125) from the Chico formation includes *Bostrychoceras* cf. *B. declive* (Gabb), *Canadoceras* cf. *C. newberryanum* (Meek), and *Submortoniceras chicoense* Trask. On Mill Creek, a collection made at Papes Place on the Arthur Banta Ranch (LSJU Coll.) includes *Hauericeras* cf. *H. angustum* Yabe, *Glyptoxoceras* sp., *Canadoceras yokoyami* (Jimbo), and *Inoceramus naumanni* Yokoyama (identified by Matsumoto).

Only a few other occurrences of *Submortoniceras* are known in California. *Submortoniceras chicoensis* (Trask) has been found at the Redmond Cut on the Western Pacific Railway 3 miles east of Altamont, Alameda County (CAS loc. 27838), and also from a railway cut between Altamont and Greenville in Alameda County (Hall and Ambrose, 1916, p. 68–71). A specimen referred to *Submortoniceras* by E. L. Packard was found while excavating for the piers of a bridge across Francisquito Creek near the

western margin of the Stanford University Golf Course.

Although *Submortoniceras* has not been found in other parts of California, the approximate stratigraphic position where it may be found is shown by its faunal associations and relationships at Chico Creek. At that place, it is associated with abundant *Baculites chicoensis* Trask and *Turritella chicoensis* Gabb below beds containing *Inoceramus subundatus* Meek and above beds containing *Baculites capensis* Woods (Matsumoto, 1959a, p. 149).

The age of the *Submortoniceras* beds may be dated fairly closely by the presence of *Submortoniceras* itself which genus has been recorded from many parts of the world in beds of early to middle Campanian age and reached its climax in the early Campanian. It may be dated, also, by the presence of *Inoceramus naumanni* Yokoyama which in Japan ranges through the Santonian into beds of early Campanian age. Associated ammonites such as *Canadoceras* and *Pachydiscus* indicate an age not older than Campanian. The presence of *Canadoceras newberryanum* (Meek) does not permit a closer determination because that species on Vancouver Island (Usher, 1952, p. 34, 68) occurs in both the Haslam and Cedar District formations which are assigned by Usher (1952, p. 39) to the lower and upper Campanian respectively. The presence of *Pachydiscus neevesi* (Whiteaves) might suggest a correlation with the Cedar District formation (Usher, 1952, p. 87, 89) except for the fact that the Cedar District formation appears to be younger than the *Metaplacenticeras* beds in California which on the basis of their entire molluscan assemblage are somewhat younger than the *Submortoniceras* beds. The absence of *Eupachydiscus* in the collections from the *Submortoniceras* beds probably has no age significance because that genus has a range considerably longer than the Campanian stage.

In summation, the *Submortoniceras* beds are definitely Campanian. They are probably lower to middle Campanian because of the association of *Submortoniceras* and *Canadoceras*, and locally of *Inoceramus naumanni* Yokoyama and because on Chico Creek they occur about 100 feet below beds that contain a molluscan assemblage that is of middle to late Campanian age.

The stratigraphic interval between the *Submortonoceras* beds and the higher *Metaplacenticeras* beds is represented at least by the *Turritella chicoensis perrini* faunule (Popenoe, 1942, p. 183–184), which is based on a certain association of pelecypods and gastropods, but probably includes beds above the range of that faunule.

The interval between the *Submortoniceras* and *Metaplacenticeras* beds is possibly represented by a faunule that occurs near the base of the Forbes formation at Sand Creek on Dobbins Ranch about 10 miles southwest of Arbuckle, Colusa County, California (CAS loc. 25730). This faunule consists of *Patagiosites arbucklensis* (Anderson), *Anapachydiscus californicus* (Yabe), *Canadoceras* cf. *C. newberryanum* (Meek), *Baculites* cf. *B. inornatus* Meek, *Inoceramus schmidti* Michael, and *I. sachalinensis* Sokolow (Matsumoto, 1960, p. 33). Of these fossils *I. schmidti* Michael and *I. sachalinensis* Sokolow in Japan and Alaska are indicative of a middle to a late Campanian age. *Patagiosites* has been reported from several parts of the world in beds of late Campanian to Maestrichtian age. For example, in the Matanuska Valley, Alaska, it occurs with *Pachydiscus ootacodensis* (Stoliczka) (USGS Mes. loc. 25327). *Anapachydiscus* is listed by Wright (1957, *in* Arkell, Kummel, and Wright, p. L380) as Coniacian to Maestrichtian, but the genus reached its climax in the Campanian.

Beds characterized by *Metaplacenticeras* are widespread in California. The species *M. californicum* (Anderson) and *M. pacificum* (Smith) have been noted in collections from (1) Enos Canyon, about 7 miles northwest of Winters, Yolo County; (2) in Pleasant Valley, Solano County; (3) at the Jordon Ranch in Arroyo del Valle in SE ¼ of sec. 11, T.4 S., R.2 E., Alameda County; (4) on the south border of Antelope Valley in northwestern Kern County; (5) near Santa Barbara in Santa Barbara County; (6) in the Santa Monica Mountains, Los Angeles County; (7) in the Simi Hills, Los Angeles County; and (8) in the Santa Ana Mountains, Orange County; (9) near Henley, Siskiyou County; (10) near Milton, Calaveras County; and (11) on Puerto Creek, Stanislaus County. Anderson (1902, p. 79, 80) reports these species from near Phoenix, Jackson County, Oregon, but specimens of *Metaplacenticeras* from that area have not been located in any museum or university.

Associated with *Metaplacenticeras* locally are many other ammonites. Near Henley, Siskiyou County, these include *Eupachydiscus haradai* (Jimbo), *Anapachydiscus deccannensis* (Stoliczka), *Pachydiscus* cf. *P. subcompressus* Matsumoto, *Desmophyllites diphylloides* (Forbes), *Gaudryceras* cf. *G. ornatum* Yabe, *Glyptoxoceras* sp., *Damesites sugatus* (Forbes),

and *Tetragonites* sp. Besides these a specimen described by Anderson (1902, p. 89, 90, Pl. 3, figs. 130–132) appears to be identical with *Didymoceras? cooperi* (Gabb). With these are associated *Inoceramus vancouverensis* Shumard and *I. subundatus* Meek (identical with *I. whitneyi* Gabb).

In the Santa Ana Mountains the *Metaplacenticeras* beds, represented by the Pleasants sandstone member of the Wiiliams formation, have furnished such ammonites as *Anapachydiscus* aff. *A. arrialoorensis* (Stoliczka) (CIT loc. 2415), *Pseudophyllites* cf. *P. indra* (Forbes) (CIT loc. 2415), *Desmophyllites* sp. (CIT locs. 3900, 3901). From these beds, or from the underlying Schulz Ranch sandstone member of the Williams formation, were obtained species of *Bostrychoceras* (CIT loc. 85) described by Anderson (1958, p. 206). Also, the specimen of *Anapachydiscus californicus* (Yabe, in Yabe and Shimizu, 1921, p. 58, Pl. 8, fig. 4) probably was obtained from the Pleasants sandstone member.

In the Simi Hills and the Santa Monica Mountains the *Metaplacenticeras* beds have furnished specimens of *Anapachydiscus* aff. *A. arrialoorensis* (Stoliczka) and *Baculites* cf. *B. inornatus* Meek. At Arroyo del Valle in Alameda County *Metaplacenticeras* is associated with *Desmophyllites diphylloides* (Forbes) and *Baculites inornatus* Meek. At Enos Canyon in Yolo County *Metaplacenticeras* is associated with *Desmophylloides diphylloides* (Forbes) and *Inoceramus subundatus* Meek.

The ammonite genera in the *Metaplacenticeras* beds are excellent evidence for a Campanian age and strongly favor a middle to late Campanian age, as has been discussed elsewhere (Peck and others, 1956, p. 1981). The beds may reasonably be correlated with the *Metaplacenticeras* beds in Japan where that genus occurs directly above *Eupachydiscus haradai* (Jimbo), *E. teshioensis* Jimbo, and *Anapachydiscus fascicostatus* (Yabe). On the basis of stratigraphic position above these species the *Metaplacenticeras* beds in Japan and California are probably slightly younger than the Haslam formation of Vancouver Island.

The ammonite *Hoplitoplacenticeras* has been found in North America only in the Cedar District formation on the south side of Sucia Island in the San Juan Island group in northwest Washington. Associated with it, according to Usher (1952, p. 16, 17), are the ammonites *Pachydiscus* cf. *P. jacquoti* Seunes, *P. neevesi* Whiteaves, *Canadoceras newberryanum* (Meek), *Desmophyllites selwynianus* (Whiteaves), *Baculites chicoenis* Trask, *B. occidentalis* Meek, and *Diplomoceras?* sp. With these ammonites are many pelecypods and gastropods (Usher, 1952, p. 17; McLellan, 1927, p. 133–135) including in particular *Inoceramus vancouverensis* Shumard and *I. subundatus* Meek. The formation has not furnished any specimen of *I. schmidti* Michael.

The ammonite faunule in the Cedar District formation of Sucia Island and Vancouver Island was placed (Usher, 1952, p. 38, 39) in the upper Campanian rather than in the lower Maestrichtian because (1) *Canadoceras newberryanum* (Meek) also occurs in the underlying Haslam formation of early Campanian age, (2) the faunule has much in common with that in Trent River formation of the Comox Basin which contains many species identical with those in the Haslam formation, and (3) *Desmophyllites selwynianus* (Whiteaves) is closely similar to *D. diphylloides* (Forbes) which is typical of Campanian rocks. Confirmation of Ushers' age assignment is furnished by Matsumoto's (1959b, p. 9) notation that *D. selwynianus* (Whiteaves) is synonymous with *D. diphylloides* (Forbes) and by the stratigraphic range of *Canadoceras* in Japan (Matsumoto, 1953, p. 295) and in Madagascar (Collignon, 1955, p. 47, 48). Nevertheless the presence of *Hoplitoplacenticeras* and of *Pachydiscus* cf. *P. jacquoti* Seunes shows that the Cedar District formation is not older than latest Campanian.

Possibly bearing on the age of the Cedar District formation is the absence of *Inoceramus schmidti* Michael. This species is common in the Trent River and Haslam formations on Vancouver Island (Usher, 1952, p. 11, 25) and is characteristic of Campanian beds (Infrahetonian and Paleohetonian) in Japan. Its absence from the Cedar District formation cannot be explained by collection failure because the formation as exposed on Sucia Island has been collected by many geologists and has furnished a very large molluscan fauna (McLellan, 1927, p. 133–135) including abundant *Inoceramus*. Its absence suggests rather that the Cedar District formation is slightly younger than the Trent River formation with which it was correlated by Usher for stratigraphic reasons, and that it occurs a little above the local range of *Inoceramus schmidti* Michael. The absence of *I. schmidti* Michael might be interpreted, therefore, as evidence that the formation is younger than Campanian if the species has as high a range on the West Coast as in Japan.

Considering all the evidence, a late Campanian age for the Cedar District formation seems more probable than an early Maestrichtian

age. The problem is not settled, but until more faunal evidence is found the age assignment made by Usher seems reasonable. Whether the Cedar District formation is exactly the same age as the *Metaplacenticeras* beds in California, as indicated by Matsumoto (1960, p. 174), is likewise not settled. Probably, however, if they were equivalent, *Hoplitoplacenticeras* would have been found in at least one of the 10 localities in which *Metaplacenticeras* has been found.

Maestrichtian

A faunule found at many places on the West Coast is characterized by the gastropod *Cophocara stantoni* Stewart, the pelecypod *Inoceramus* aff. *I. shikotaensis* Nagao and Matsumoto, and the ammonites *Pachydiscus ootacodensis* (Stoliczka), *P. egertoni* (Forbes), *P.* (*Neodesmoceras*) *catarinae* (Anderson and Hanna), *Anapachydiscus peninsularis* (Anderson and Hanna), *Menuites* cf. *M. menu* (Forbes), *Didymoceras* (*Nostoceras?*) *vancouverense* (Gabb), *Baculites rex* Anderson, *Eubaculites ootacodensis* (Stoliczka), *Solenoceras* sp., *Diplomoceras* sp., and a tuberculate variant of *Neophylloceras hetonaiense* Matsumoto. It has been identified near Santa Catarina Landing in Baja California (Anderson and Hanna, 1935), near San Diego, California, in the Simi Hills in Los Angeles County, near Wheeler Gorge in Ventura County, in the western part of the Santa Ynez Range in Santa Barbara County, at many places along the western side of the San Joaquin Valley, near Martinez in Contra Costa County, locally on the western side of the Sacramento Valley in Yolo and Solano counties, on Vancouver Island, in the southeastern part of the Talkeetna Mountains of Alaska, and at the head of the Alaskan Peninsula.

Its occurrences in California have been fully documented by Matsumoto (1960, p. 40, 44, 46–49, 54–55, 58–63, 69, 71, 73) and are not repeated here except to note that along the west side of the San Joaquin Valley it is characteristic of the highest parts of the Panoche formation and that elements of the faunule occur locally in the lower part of the Moreno formation.

This faunule is correlated with the Maestrichtian beds of Japan, mainly on the basis of the ammonites belonging to *Pachydiscus* (*Neodesmoceras*). Matsumoto (1960, p. 177–178) suggests that the faunule is of early Maestrichtian age but does not exclude the possibility of a late Campanian to early Maestrichtian age. He notes, however, that one of the most common species in the faunule, *Baculites rex* Anderson, occurs stratigraphically above *Baculites occidentalis* Meek and *Metaplacenticeras* (Matsumoto, 1959a, p. 142), so the faunule is not likely to be older than latest Campanian.

Elements of the same faunule, including in particular *Pachydiscus ootacodensis* (Stoliczka) have been found on Vancouver Island in the Lambert formation and in the lower part of the Northumberland formation. Some of the species of *Didymoceras* and *Diplomoceras* from these formations may be synonymous with described species from Baja California, but other ammonites, such as *Pachydiscus suciaensis* (Meek), have not yet been definitely identified from areas south of Vancouver Islands in beds characterized by *Pachydiscus catarinae* (Anderson and Hanna). Possibly, however, the beds in California and Baja California characterized by *Pachydiscus catarinae* are of slightly different age from the Lambert and Northumberland formations. This possibility is suggested by the fact that at the head of the Alaskan Peninsula in the Kamishak Hills *P. suciaensis* (Meek) is associated with *P. subcompressus* Matsumoto which species in Japan characterize beds of middle Maestrichtian age.

The Moreno formation on the basis of stratigraphic position should be of middle to late Maestrichtian age. However, the late Maestrichtian zone of *Sphenodiscus* has not been identified in the West Coast. It is possibly represented in the Moreno formation above beds containing *Pachydiscus* (*Neodesmoceras*) or in the highest Cretaceous beds that have not furnished ammonites. Ammonites are reported to be uncommon in the Moreno formation but have been found in it at various levels as high as the Marca shale member. They belong mostly to the uncoiled genera *Didymoceras*, *Solenoceras*, *Glyptoxoceras*, *Baculites*, *Eubaculites*, and *Diplomoceras*. Normally coiled ammonites include *Neophylloceras*, *Pachydiscus*, and *Phyllopachyceras*. The highest-ranging ammonites in the Moreno formation are *Baculites rex* Anderson, *Eubaculites ootacodensis* (Stoliczka), *Diplomoceras* sp., and *Neophylloceras hetonaiense* Matsumoto (Matsumoto, 1960, p. 44, Pl. 1). These furnish a correlation with the Maestrichtian of Japan but do not show what part of the Maestrichtian is represented.

Correlation of Foraminiferal with Molluscan Zones

The foraminiferal zones established by Goudkoff (1945) for the Cretaceous beds in California, largely on the basis of subsurface data,

were correlated by him with various formations on the west side of the San Joaquin Valley and along the margins of the Sacramento Valley. His H zone is correlated with formations that have furnished Cenomanian or early Turonian ammonites or that are assigned to those stages because they underlie beds of middle to late Turonian age. For example, the H zone probably includes the "lower Waltham" shale of Waltham Canyon from which the Cenomanian ammonite *Forbesiceras* has been obtained (LSJU Coll.).

His G-2 zone is correlated with beds that contain ammonites of middle to late Turonian age such as Members II, III, and the lower part of Member IV in the Redding district, and the Sites formation and most of the Yolo formation on the west side of the Sacramento Valley. The common ammonites in these beds are *Subprionocyclus*, *Collignoniceras*, *Romaniceras*, and *Otoscaphites*. The top of the G-2 zone coincides with the top of the *Glycymeris pacificus* zone of Popenoe (1942, p. 181).

Goudkoff's G-1 zone was correlated on the basis of microfossils with the upper part of Member IV and all of Member V in the Redding area and with the Funks formation on the west side of the Sacramento Valley. Member IV in the Redding area has furnished the Coniacian ammonites *Peroniceras* and *Prionocycloceras*. Members IV and V both contain *Baculites schencki* Matsumoto (1959a, p. 113–118), which occurs elsewhere in the basal 700 feet of the Cretaceous section on Chico Creek and in the Funks formation. From Member V Matsumoto (1960, p. 10–12) records such species as *Baculites capensis* Woods, *Inoceramus naumanni* Yokoyama, and *I.* cf. *I. cordiformis* Sowerby of late Coniacian to Santonian age. On the basis of these mollusks Goudkoff's G-1 zone is correlated with the Coniacian and at least part of the Santonian stages.

Goudkoff's F-2 zone was identified by him in the Guinda formation and in small adjoining parts of the Funks and Forbes formations. The Guinda formation has not yet furnished mollusks that are useful in correlation with European stages, but on the basis of stratigraphic position it should be of late Santonian and early Campanian age. Probable equivalents of the F-2 zone on Chico Creek, as indicated by microfossils, include beds containing *Submortoniceras* and *Turritella chicoensis* Gabb and some underlying beds containing *Baculites capensis* Woods (identified by Matsumoto). This baculite in Europe occurs in the upper Coniacian and the Santonian. (*See* Annotation 45.) Goudkoff (1945, p. 991, Figs. 62, 72) shows that the F-2 zone in the subsurface pinches out rapidly eastward and becomes sandier westward.

The presence of *Submortoniceras* in the *Turritella chicoensis* zone on Chico Creek shows that the top of that zone is not younger than Campanian and probably not younger than middle Campanian. A Campanian age is confirmed by the presence of *Canadoceras* cf. *C. multisulcatus* (Whiteaves) in the Santa Ana Mountains about 200 feet below the top of the Ladd formation (CIT loc. 1053) in the upper part of the *Turritella chicoensis* zone (Popenoe, 1942, p. 177–179).

Goudkoff's F-1 zone was identified by him in the Forbes formation along the west side of the Sacramento Valley and in the "Joaquin Ridge" sandstone member of the Panoche formation along the west side of the San Joaquin Valley. It has since been identified in many places in California in beds characterized by *Metaplacenticeras*. This ammonite in California and Japan occurs near the top of a thick sequence of Campanian age.

Goudkoff's E zone according to him does not outcrop in the Sacramento Valley but is present in the subsurface. He identifies it on the outcrop in the San Joaquin Valley in the lower part of the Ragged Valley shale member of the Panoche formation. His next higher D-2 zone is identified in the upper part of the Ragged Valley shale member which has furnished an ammonite faunule consisting of *Pachydiscus ootacodensis* (Stoliczka), *P. catarinae* (Anderson and Hanna), and *Baculites rex* Anderson. This faunule is considered to be of early Maestrichtian age for reasons discussed under the heading Correlations with European Stages.

Goudkoff's D-1, C, and B zones may likewise be correlated with the Maestrichtian because they overlie the E zone of early Maestrichtian age and because their outcrop equivalents contain Cretaceous ammonites. If the A-2 zone is equivalent to the Garzas sand as Goudkoff (1945, p. 979) indicates, it may also be assigned to the Cretaceous because of the presence of the mosasaur described by Camp (1942).

Annotations

1. A rudist-bearing limestone containing *Radiolites?* has been reported by Keller (1928, p. 333) from the eastern part of the Sierra del Rajón, 45 km south-southeast of Altar, Sonora. This limestone could be of Albian age or of early Late Cretaceous age. An Albian age is favored by its northern position, considering that all rudist-bearing limestones at a similar

latitude in northeastern Mexico are Albian.

Oyster-bearing beds noted by Keller (1928, p. 333) 12 km west of Santa Ana, 20 km northwest of Altar, and on Cerro Copete northeast of Hermosillo were considered by him as probably Cretaceous. Arellano (1946, p. 10) collected some large flat oysters from the Sierra de Santa Rosa (Ocuca), about 40 km west of Santa Ana. Imlay (written communication dated January 11, 1945) examined them and noted that similar large oysters are common in the Bisbee group of Arizona and Sonora. However, a reliable age assignment cannot be made solely on the basis of such oysters.

2. A Valanginian or possibly Hauterivian age determination was made by Burckhardt (1930, p. 150) for some pelecypods collected near Santa Ana and Horcasitas, Sonora. He lists *Ctenostreon* sp., *Exogyra* sp., several species of *Trigonia*, and a large, thick-shelled oyster. Some of the Trigonias are compared with species of Neocomian age. His age determination may be questioned because similar-appearing Trigonias have been found in rocks of quite different ages and because the other genera listed could represent any time from the Lias to the end of the Lower Cretaceous.

3. The Valle Salitral formation according to Federico Mina U (1957, p. 159–162) outcrops on the west side of the Vizcaino basin from the Peninsula de Vizcaino southeast about 180 km to Punta Abreojos. It is about 3000 m thick and consists of shale, sandy shale, sandstone, and conglomerate. The lower 1500 m yielded large specimens of the ammonite *Submortoniceras* (identified by Imlay). The presence of this genus is good evidence that the enclosing beds are of Campanian age and are probably of early to middle Campanian age.

4. The Eugenia formation according to Federico Mina U (1957, p. 152, 156–158) outcrops only near Punta Eugenia at the northern end of the Peninsula de Vizcaino, but on a map he indicates that it outcrops farther northwest on Natividad Island and on Cedros Island. The formation is about 3000 m thick, consists of sandstone, shale, and conglomerate, and is overlain with angular unconformity by the Valle Salitral formation. Its age is unknown according to F. Mina U (1957, Fig. 1, on p. 152), but he mentions the presence of ammonite fragments and assigns the beds tentatively to the Lower Cretaceous.

5. The Rosario formation (Beal, 1924, p. 49; 1948, p. 40–44) of Baja California has furnished a large molluscan fauna including, in particular, the gastropod *Cophocara stantoni* Stewart, the pelecypod *Inoceramus shikotaensis* Nagao and Matsumoto, and such ammonites as *Pachydiscus* (*Neodesmoceras*) *catarinae* (Anderson and Hanna), *P. ootacodensis* (Stoliozka), and *Baculites* aff. B *occidentalis* Meek (Anderson and Hanna, 1935), *Pseudophyllites indra* (Forbes), and the rudist *Coralliochama orcutti* White (Durham and Kirk, 1950, p. 1537). The formation was assigned a late Campanian age by Anderson and Hanna (1935), p. 18) on the basis of ammonites and by Bandy (1951; 1952, p. 1320) on the basis of foraminiferal studies. Durham and Kirk pointed out that the ammonites were similar to species from India that are considered of Maestrichitan age. Later studies by Usher (1952, p. 39–41) of the Late Cretaceous ammonites from Vancouver Island, by Matsumoto (1951, p. 19–26), and by Matsumoto and Saito (1954, p. 87–91) of the ammonite *Pachydiscus* in Japan indicate rather strongly that the pachydiscid ammonites found in the Rosario formation are of early Maestrichtian age. As the European stages were established primarily on the basis of molluscan faunas, the Rosario formation and equivalent beds in California are herein considered as early Maestrichtian in spite of the evidence of the microfaunas.

Elements of this faunule are widespread in California. The characteristic ammonites occur at Point Loma in San Diego County (Grant and Hertlein, 1944), at the top of the Cretaceous sequence in the Simi Hills (Popenoe, 1954, p. 17, 20), in the Jalama formation of the western part of the Santa Ynez Mountains (Dibblee, 1950, p. 22–24, 38), and in the upper part of Ragged Valley shale member of the Panoche formation in the Coalinga–Warthan Canyon area. The rudist *Coralliochama orcutti* White occurs at Point Loma and La Jolla in San Diego County (Durham and Kirk, 1950), in the Schulz Ranch sandstone member of the Williams formation in the Santa Ana Mountains (UCLA collections), in the Debris Dam sandstone in the Santa Barbara area (Page *et al.*, 1951, p. 1738), in the Gualala formation of the Point Arena area, and in the Santa Lucia Range (Taliaferro, 1944, p. 502). This rudist was once considered of Turonian age (Anderson and Hanna, 1935, p. 7), but it has been found with ammonites of middle Campanian to Maestrichtian age (Durham and Kirk, 1950). Its range, therefore, is similar to that of *Coralliochama* in Mexico.

6. The Alisitos formation (Santillan and Barrera, 1930, p. 9–14) (equals San Fernando formation of Beal, 1924, p. 52) contains a large

fauna that permits a correlation with the Glen Rose formation of Texas (Allison, 1955, p. 404), which is of early and early middle Albian age. This correlation has been confirmed by the discovery of the ammonite *Douvilleiceras* a quarter of a mile west of the Buena Vista Ranch on the west side of the Sierra San Pedro Mártir at Lat. 31°00′ N., Long. 115°53′ W. (USGS Mes. Coll at Menlo Park). The Alisitos formation is reported to be overlain with angular unconformity by the Rosario formation (Allison, 1955, p. 402–403). Beal (1948, p. 108, 109) reported that the San Fernando formation is extensively intruded by basic dikes, whereas the Rosario formation is not.

7. The Pleasants sandstone member of the Williams formation in the Santa Ana Mountains is characterized by the ammonite genus *Metaplacenticeras* which is one of the most widespread and easily recognized ammonites in the Cretaceous of California. With it are associated *Anapachydiscus* cf. *A. arrialoorensis* (Stoliczka), *A. californicus* (Yabe), *Pachydiscus buckhami* Usher, *Desmophyllites diphylloides* Forbes, *Pseudophyllites* cf. *P. indra* (Forbes), and the uncoiled ammonites *Baculites* cf. *B. inornatus* Meek and *Bostrychoceras*. This faunule in nearby parts of southern California occurs near the top of the Cretaceous sequence in the Santa Monica Mountains and near the base of the exposed Cretaceous in the Simi Hills (Popenoe, 1942, p. 184–186; 1954, p. 16–20). The same faunule characterized by *Metaplacenticeras* is widespread elsewhere in California. A full discussion of its age significance is given under the heading Correlation with European Stages.

8. The Holz shale member of the Ladd formation in the Santa Ana Mountains is 1000 -1500 feet thick and is characterized in its lower 200 feet by the upper part of the *Idonearca gravida* faunule of late Turonian age (Popenoe, 1942, p. 182). From the middle of the member to within 200 feet or less of the top it is characterized by the *Turritella chicoensis* faunule (Popenoe, 1942, p. 183). About 100 feet below the upper limit of this faunule was a specimen of the ammonite *Canadoceras* (CIT loc. 1053) of Campanian age. The upper 200 feet of the Holz shale member in some sections contains the *Turritella perrini* faunule (Popenoe, 1942, p. 184), which is dated as middle Campanian on the basis of its stratigraphic position above the ammonite *Canadoceras* and below the *Metaplacenticeras* beds in the Williams formation. Popenoe (1942, p. 177) indicates that the *Turritella perrini* faunule is missing locally in the Santa Ana Mountains which suggests that the contact of the Holz shale member with the overlying Williams formation may represent a minor disconformity. Evidently on the basis of its fossil content the Holz shale member of the Ladd formation ranges in age from late Turonian to middle Campanian provided that the Turonian fossils in its lower 200 feet have not been reworked, which is not probable, or that the member does not include disconformities.

9. The Baker Canyon conglomerate member of the Ladd formation has furnished many mollusks belonging to the upper part of the *Glycymeris pacificus* faunule of Popenoe (1942, p. 181, 182), including the ammonites *Subprionocyclus* and *Scaphites* (*Otoscaphites*) of middle to late Turonian age. These ammonites, and locally such ammonites as *Collingnoniceras*, *Romaniceras*, *Coilopoceras*, and *Mesopuzosia*, are widespread in California and Jackson County, Oregon. A full discussion of the age significance and distribution of the ammonites is given under the heading of Correlation with European Stages.

10. Fossils have not been found in the Trabuco formation in the Santa Ana Mountains or in the similar-appearing red conglomerate at the base of the Cretaceous sequence in the Santa Ana Mountains. These conglomerates are arbitrarily assigned to the Turonian because they appear to be conformable with overlying beds (Popenoe, 1941, p. 738, 744) of middle to late Turonian age, but they could be older in part.

11. Cretaceous rocks exposed in Wheeler Gorge northeast of Wheeler Hot Springs, Ventura County, consist of sandstone, shale, and conglomerate about 5000 feet thick. From these rocks a short distance below the lower of two sets of tunnels have been obtained a large pachydiscid ammonite and several specimens of *Inoceramus*. According to Tatsuro Matsumoto (letter of Nov. 16, 1957, to W. P. Popenoe) the ammonite "might be *Pachydiscus* (*Neodesmoceras*) sp., but the specimen is too poorly preserved to be accurately identified . . .. In association . . . is a crushed *Inoceramus* of the type of *I. shikotanensis* Nagao and Matsumoto (equals *I. pacificus* Anderson and Hanna *non* Woods)".

The association of such an *Inoceramus* with a large smooth pachydiscid ammonite suggests a correlation with the Upper Hetonian stage of Japan which is correlated with the Maestrichtian stage of Europe. As the specimens from Wheeler Gorge were obtained near the middle

1519, column 2, line 28 from bottom, *for* Santa Ana Mountains, *read* Santa Monica Mountains

of a thick sequence the Campanian is probably represented also. The fossil evidence is not good enough for a precise determination but is sufficient to show that the sequence in Wheeler Gorge is of late Late Cretaceous age.

12. Beds of middle to late Valanginian age, characterized by *Buchia crassicollis* (Keyserling), are widespread in western California from Santa Barbara County northward to Trinity County. They are not present in the eastern sides of the San Joaquin and Sacramento valleys, in the Hornbrook area of Siskiyou County, in the Redding area of eastern Shasta County, or in the Ono area of western Shasta County. Their main occurrences have been described by Anderson (1938b, p. 49–55) and Irwin (1957, p. 2292, 2293). Generally the beds are easily recognized by the presence of abundant, plump, nearly equivalve *Buchia*. Locally in Tehama County other mollusks including ammonites are common in some beds. South of Tehama County few ammonites have been found. Among these is a specimen of *Kilianella* from the Berkeley Hills (Lawson, 1914, p. 8) and an immature *Thurmanniceras*, probably belonging to *T. jenkinsi* Anderson (1938b, p. 165), obtained from the Warthan (Waltham) Creek Valley in Fresno County.

The Niles Canyon formation of Hall (1958, p. 8) in the Pleasanton quadrangle is presumably also of Valanginian age as it is reported to contain *Buchia sp.*, *Berriasella* ? sp., and *Phylloceras knoxvillense* Stanton. Its thickness of 4000–7500 feet is considerably greater, however, than any other Valanginian sequence recorded from California.

13. The fossils present in the Pendola shale and in the Debris Dam sandstone, such as *Trigonia inezana* Packard and *Perissitys brevirostris* (Gabb), indicate a late Late Cretaceous age (Page *et al.*, 1951, p. 1742, 1744). Also, their position above shales containing *Coralliochama orcutti* White (Page *et al.*, 1951, p. 1738) is good evidence that they are late Campanian or Maestrichtian in age as that species in California and Baja California is commonly associated or occurs near beds containing *Pachydiscus catarinae* (Anderson and Hanna) (Durham and Kirk, 1950, p. 1537). This age is confirmed by the presence of *Baculites rex* Anderson (Matsumoto, 1959a, p. 142) in the Debris Dam sandstone.

14. A thick sequence of sandstone, shale, and conglomerate in the Nipomo and Branch Mountain quadrangles in the southern part of the La Panza Mountains has been assigned by Taliaferro (1943a, p. 131; 1943b, p. 199) to the Upper Cretaceous without presentation of fossil evidence. He indicates that these Upper Cretaceous rocks rest unconformably on beds of Valanginian age. The same sequence of Upper Cretaceous rocks is present in the La Panza and Pozo quadrangles in the northern part of the La Panza Mountains. The presence of beds of middle Campanian to late Campanian age in the San Rafael Mountains is shown by the presence of *Inoceramus subundatus* Meek in Sisquoc Canyon (LSJU Coll.). Lithologically these beds appear to be a southern extension of the Asuncion formation.

15. The Asuncion formation, according to Taliaferro (1944, p. 501), has furnished fossils only in its upper 1500–2500 feet, which comprises one-fourth to one-third of the formation. These fossils have been examined by a number of paleontologists whose opinions regarding ages, or correlations, have been summarized by Taliaferro (1944, p. 502–508). He concludes that the information available indicates late Senonian and Maestrichtian ages. He emphasizes that the lower 3000–7000 feet of the formation have not furnished fossils and are dated as Upper Cretaceous only because they lie unconformably on the Jack Creek formation.

16. The age of the Jack Creek formation according to Taliaferro (1944, p. 482) is based on some belemnites and *Inoceramus* that were examined by S. W. Muller and assigned by him to the "Upper Cretaceous, probably 'early Chico'." Taliaferro accepted this age assignment, but noted the Jack Creek formation is separated from the overlying Asuncion formation by an unconformity involving folding, faulting, uplift, and the removal of thousands of feet of rocks over wide areas. By comparisons with Cretaceous sequences in the Diablo Range, Taliaferro (1944, p. 510–512) concluded that the unconformity was developed late in the Turonian, or after that stage, and therefore that the Jack Creek formation was of Cenomanian and Turonian ages. In contrast to this age assignment, the writers consider that the presence of belemites is fairly good evidence that the Jack Creek formation is older than the Late Cretaceous, because belemnites are almost unknown in beds of that age on the Pacific Coast, but are rather common in Lower Cretaceous beds.

17. The Upper Cretaceous sequences in the Cholame quadrangle have furnished fossils showing that the age range is from Cenomanian to Maestrichtian. From the southeastern part of the quadrangle have been obtained *Desmophyllites diphylloides* (Forbes), *Tetragoniles*

popelensis Anderson, and *Baculites rex* Anderson (Matsumoto, 1960, p. 63) of late Campanian to early Maestrichtian age. The Campanian ammonite *Metaplacenticeras* was obtained from the south side of Antelope Valley in northwestern Kern County (CAS Coll.). North of Antelope Valley near Devil's Den in Kern County the local Cretaceous sequence contains microfossils that belong to Goudkoff's zones C, D, and uppermost E which are correlated with the late Campanian and the Maestrichtian stages. Interestingly, the upper part of the sequence near Devil's Den contain abundant worn fragments of Valanginian belemnites in secs. 2 and 32, T. 25 S, R. 18 E. (UCLA collections). Also in the west half of sec. 32, Valanginian *Buchia* has also been found with the Valanginian belemnites (Anderson, 1938b, p. 54, 226; CAS loc. 27605) in the Moreno formation. These megafossils are obviously derived from Valanginian beds, but, according to Clarence Hall (Personal communication, November, 1957), such beds are not known to be exposed in this part of the Cholame quadrangle.

Still farther north in the Cholame quadrangle, west of Reef Ridge in Kings County, Stewart (1946, p. 89) collected fossils (Field no. 91) that have been identified by Popenoe as late Senonian, probably Campanian. In the same area from a little below the Tertiary contact have been obtained ammonites that Matsumoto (1960, p. 62) considers to be late Campanian to Maestrichtian. He lists *Baculites rex* Anderson from 100 feet below the contact and *Baculites* cf. *B. inornatus* Meek and *Neophylloceras ramosum* (Meek) from 200 feet below the contact. Farther northwest, to the west of Reef Ridge in Fresno County, Stewart (1946, p. 88) collected other fossils (Field no. 97) that Popenoe identified as of Turonian age. These are of particular interest because they occur according to Taliaferro (letter dated April 30, 1941, to W. P. Popenoe) about 500–600 feet below the base of the Eocene Avenal sandstone and near the top of a Cretaceous sequence that is about 9720 feet thick.

18. Fossil evidence showing that only the lower part of the original Moreno formation of Anderson and Pack (1915, p. 46) at the type locality is of Late Cretaceous age has been discussed in several papers (Stewart, Popenoe, and Snavely, 1944; Goudkoff, 1945, p. 967–982; Payne, 1951, p. 11; Schoellhamer and Kinney, 1953). On the basis of megafossils the contact between the Cretaceous and the Tertiary is either at the base of the Cima sandstone lentil of the Dos Palos shale member or between the lentil and the top of the Marca shale member. On the basis of microfossils the lower part of the Dos Palos shale member was correlated with the Cretaceous by Goudkoff (1945, p. 982). The Moreno is correlated with the Maestrichtian stage for reasons discussed under the heading Correlation with European Stages.

19. The 20,000–30,000 feet of beds included in the Panoche formation have never been subdivided so that the units could be mapped over a considerable area. For the sequence in the Alcalde Hills J. Q. Anderson (unpublished report) proposed a set of member names that are useful locally but apparently cannot be extended northward to the type locality of the Panoche formation in the Panoche Hills. Unfortunately the member names were never properly proposed in publication and hence are shown in the correlation chart in quotation marks.

On the basis of foraminiferal studies Goudkoff (1945, p. 962-966) has shown that the top of the Panoche formation as mapped in the Alcalde Hills and the Panoche Hills corresponds with the top of his D-1 Zone. In the Ortigalito Peak quadrangle (Briggs, 1953, p. 34) it corresponds with the top of his D-2 Zone, and from Los Baños Creek northward to Mount Diablo it corresponds with the top of his F-1 Zone.

The mollusks found in the Panoche formation range in age from Cenomanian to early Maestrichtian according to the evidence presented by Anderson (1958, p. 56–60) and Matsumoto (1960, p. 41–47, 50–59). This evidence has been summarized under the heading Correlations with the European Stages.

20. The name Wisenor formation was proposed by Briggs (1953, p. 20–22) for more than 1800 feet of dark shale and thin beds of hard carbonaceous sandstone lying unconformably below the Panoche formation in the area east of Ortigalito Peak. He included in the formation similar strata exposed along the Diablo Range such as at Hospital Creek and Corral Hollow. He assigned these beds to the Horsetown stage as defined by F. M. Anderson on the basis of an oral communication from Taliaferro.

Most of the evidence for this assignment is not yet published. Certain genera of Early Cretaceous cephalopods mostly of Albian age were mentioned by Anderson (1938b, p. 38, 54, 67) as occurring discontinuously along the eastern flank of the Diablo Range, mainly north of the Panoche Hills. He specifically mentioned the presence of *Cleoniceras* and

Puzosia at Hospital Creek and Corral Hollow in the northern part of the Diablo Range.

The specimens that Anderson referred to *Cleoniceras* and *Puzosia* are now placed in *Leconteites* and *Puzosigella* and are considered to be of early Albian age. Their presence in Hospital Canyon, San Joaquin County, is confirmed by collections in the U. S. Geological Survey that were obtained 50–100 feet above the contact with Franciscan-like rocks. The collections (USGS Mes. locs. 18822, 18824, 18826) include *Puzosigella mulleri* (Anderson), *P.* cf. *P. rogersi* (Hall and Ambrose), *Leconteites lecontei* (Anderson), and *L. modestum* (Anderson). Other collections from Hospital Canyon have furnished *Phyllopachyceras* sp. and *Beudanticeras hulense* Anderson (Matsumoto, 1960, p. 53). The stratigraphic relationships of these fossils to the base of the Panoche formation is not known.

Elsewhere in the Diablo Range the presence of the ammonite *Mortoniceras* proves that beds of late Albian age are present locally. The genus has been found 9 miles northwest of New Idria in San Benito County (CAS loc. 31229) and is possibly represented by a fragment obtained on the north side of Wartham (Waltham) Creek in the Alcade Hills. The Albian is represented also by *Puzosigella rogersi* (Hall and Ambrose) found in conglomeratic beds 1 mile northeast of Mercy Hot Springs in the Panoche quadrangle (USGS Mes. loc. 6957). In addition some Albian ammonites have been found in the basal conglomeratic beds of the Panoche formation in the Panoche Hills. They include *Leconteites lecontei* (Anderson), *Beudanticeras* (*Brewericeras*) *hulense* Anderson, *Bhimaites* sp., and *Desmoceras* (*Pseudouhligella*) sp. (Matsumoto, 1960, p. 41). The ammonites found in the conglomerates are probably derived from older beds.

Farther north in the Pacheco Pass quadrangle the Albian appears to be absent as Fred Schilling and David Jones collected the early Turonian fossils *Kanabiceras* and *Inoceramus labiatus*, (Schlotheim) a short distance above beds contains *Buchia crassicollis* (Keyserling) and *B. piochii* (Gabb) (David Jones, written communication, October 28, 1959).

At Corral Hollow in secs, 34, 35, and 36, T. 3 S., R. 3 W., Alameda County, the beds that Briggs (1953, p. 20–22) referred to the Wisenor formation consist of 500 feet or less of dark-gray to black concretionary shales (Huey, 1948, p. 23, 24) that have furnished the ammonite *Puzosigella rogersi* (Hall and Ambrose), *P. teslaensis* (Pemberton), *Leconteites lecontei* Anderson, and species of *Marshallites*. These fossils must have been collected from different levels as *Leconteites* and *Puzosigella* are of early Albian age, and *Marshallites* is of Cenomanian to Turonian age. The particular species of *Marshallites* present resemble *M. theobaldianus* (Stoliczka) and *M. papillatus* (Stoliczka) of Cenomanian age.

21. The term "Moreno Grande formation" was proposed by Huey (1948, p. 31, 32) for beds in the Diablo Range that had been mapped as the Moreno formation by Anderson and Pack (1915), but which according to Huey included older beds than are present in the type section of the Moreno formation. Huey did not name a type locality for his "Moreno Grande" formation, and hence the term is used here in quotations. He indicated, however, that the "Moreno Grande" formation in the Tesla area attains a maximum thickness of 650 feet, is locally absent, and contains a microfauna that is correlative with Goudkoff's D-2 zone.

The underlying Panoche formation of Huey has furnished the late Campanian ammonite *Metaplacenticeras* (Huey, 1948, p. 28) about 2500 feet below its top in the SE¼ Sec. 11, T. 4 S., R. 2 E., near Arroyo de Valle. This genus is associated with other ammonites and with *Inoceramus* of middle to late Campanian age. From the upper part of the section at Arroyo de Valle was obtained a specimen of *Baculites rex* Anderson (Matsumoto, 1959a, p. 142) which suggests a late Campanian or Maestrichtian age younger than *Metaplacenticeras*. Elsewhere in the Tesla quadrangle an early Campanian age is indicated for some beds by the presence of *Submortoniceras chicoense* (Trask) from the railway cut on the Western Pacific Railway east of Altamont (CAS loc. 27838) in the NE¼ SE¼ Sec. 27, T. 2 S., R. 3 E. This species includes *S. templetoni* (Hall and Ambrose) reported to have been obtained from a railway cut between Altamont and Greenville.

Fossils of late Turonian age have been found in the lower part of the Panoche formation of Huey southwest of Arroyo de Valle in the NE¼ Sec. 23, T. 4 S., R. 2 E. (LSJU loc. 2735). The age is based on the ammonite *Subprionocyclus normalis* (Anderson) (Matsumoto, 1960, p. 71).

Huey (1948, p. 28, 29) mentions the presence of a still older Late Cretaceous faunule at his locality XI in the SE¼ Sec. 29, T. 4 S., R. 3 E. However, one of the ammonites listed is *Pachydesmoceras colusaense* (Anderson) (1902, p. 96, Pl. 5, figs. 128, 129), which occurs with late Albian ammonites near Sites in Colusa County and on the North Fork of Cottonwood

Creek in Shasta County (Anderson, 1958, p. 26, 236).

The Del Valle formation was proposed by Hall (1958, p. 11–13) for about 9000 feet of sandstone, siltstone, and shale occupying only about 4 square miles of the Pleasanton quadrangle. Hall notes that the formation extends into the Tesla quadrangle, and he lists the same ammonites at the same localities as in the Panoche formation of Huey. Evidently Hall intends that his Del Valle formation should replace the term Panoche formation in the Pleasanton and Tesla quadrangles.

22. Cretaceous strata north of Franklin Canyon and about 1 mile southwest of Martinez, Contra Costa County, have yielded a large molluscan fauna that indicates a Maestrichtian age. It includes *Cophocara stantoni* Stewart, "Pugnellus" *hamulus* Gabb, *Meekia sella* Gabb, *Calva varians* (Gabb), and a number of other species that elsewhere in California occur in the Moreno formation of the Los Banos and Mt. Diablo areas and in the "Ragged Valley" shale member of the Panoche formation above the level of *Pachydiscus* (*Neodesmoceras*) *catarinae* Anderson and Hanna. One of the ammonites recorded from the Martinez area is *Eubaculites ootacodensis* (Stoliczka) (Matsumoto 1959a, p. 166–171).

23. The probable presence of Turonian in the Martinez area is suggested by the presence of *Idonearca gravida* (Gabb) collected by C. E. Weaver from the arsenal grounds at Benicia, Solano County, across the Carquinez Straight from Martinez, and identified by Popenoe. The presence of the Cenomanian is proven by the ammonite *Mantelliceras lecontei* (Anderson) (Anderson, 1938b, p. 242) obtained 1 mile southeast of Crockett.

24. An occurrence of *Buchia piochii* (Gabb) from near the New Almaden mine was reported by Gabb (1869, p. 247). That species proves the presence of beds of latest Jurassic age if correctly identified. Some limestones in the Franciscan formation near the New Almaden have furnished microfossils that Küpper (1955), p. 112) considers to be of Cenomanian age. Edgar Bailey of the U. S. Geological Survey has found within the Franciscan formation some fragments of nerineid gastropods that could be Jurassic or Cretaceous. He has found, also, a fragmentary echinoid which has been identified by H. Barraclough Fell of Victoria University, New Zealand, with the genus *Stereocidaris* (written communication dated Sept. 15, 1959, to Porter M. Kier of the U. S. National Museum). According to Fell "The specimen is a very well characterized species of *Stereocidaris*" and is "closer to *Stereocidaris merceyi* (Cotteau) than to any other species." Its age "cannot be older than Cenomanian and may well be late as Senonian."

25. The name Berryessa formation was introduced by Crittenden (1951, p. 33–35) for 1000–2000 feet of sandstone, siltstone, and shale overlying the Oakland conglomerate of definite Valanginian age, and underlying beds of Tertiary age. He did not find any fossils in the formation but quotes lists of fossils collected by other geologists (Crandall, 1907, p. 41–43). These fossils indicate ages ranging from late Jurassic into early Cretaceous. Evidently some of the fossils must be misidentified, or the collections are mixed as some of the associations reported have never been found elsewhere. However, as *Buchia* was found at most of the localities, Crittenden's Berryessa formation at those localities is not younger than Valanginian. Whether any part of the formation is younger than Valanginian is not known.

26. Upper Cretaceous beds were found on the Stanford University campus while excavating for piers of a bridge across Francisquito Creek near the western margin of the Stanford golf course. These were identified by Earl L. Packard as follows:

Cymatoceras aff. *C. suciaensis* (Whiteaves)
Neophylloceras aff. *N. lambertense* Usher
Gaudryceras aff. *G. tenuiliratum* Yabe
Submortoniceras cf. *S. chicoensis* (Trask)
Baculites inornatus Meek

These fossils are poorly preserved, but the general assemblage indicates a Campanian age. This age determination has been confirmed by Matsumoto (1960, p. 73), on the basis of mollusks, and by Joseph Graham of Stanford University, on the basis of the microfossils (David Jones, written communication, October 28, 1959).

27. The Pigeon Point formation extends nearly continuously for 10 miles along the Pacific Coast from Pescadero Point southward, consists mostly of brown sandstone, is about 8500 feet thick, and contains fossils that indicate Campanian to Maestrichtian ages (Hall, Brooks, and Jones, 1959 p. 2858, 2859). This age determination is based on the occurrence of *Glycymeris veatchi* (Gabb), *Turritella chicoensis pescaderoensis* Arnold (1908, p. 347, Pl. 31), and the ammonite *Didymoceras* sp. A Campanian age for part of the formation is also proved by an assemblage of Foraminifera.

28. The ammonite *Douilleiceras* of Albian

age (Schlocker and others, 1954) and many Foraminifera of Cenomanian age (Thalmann, 1942; 1943; Church, 1952; Kupper, 1955) have been found in the Franciscan formation in its type locality on the San Francisco Peninsula. In the same formation on the north side of San Francisco Bay *Mantelliceras* of Cenomanian age has been found (Hertlein, 1956). *Inoceramus schmidti* Michael of late Campanian age has been found near Novato in rocks previously mapped as Franciscan, but probably referable to another formation (Durham and Jones, 1959, p. 1716).

29. The Gualala group has been assigned a Maestrichtian age by Durham and Kirk (1950, p. 1537) because it contains *Coralliochama orcutti* White which occurs elsewhere in southernmost California at Point Loma and La Jolla and in Baja California at Todos Santos Bay associated with the ammonite *Pachydiscus catarinae* (Anderson and Hanna) Some of the other mollusks associated with *C. orcutti* White in the Gualala group (Weaver, 1944, p. 16) also occur in Baja California at Todos Santos Bay and 15 miles south of Rosario (Anderson and Hanna, 1935, p. 7, 8; White, 1885b, p. 8). The last locality also contains *Inoceramus shikotanensis* Nagao and Matsumoto (Matsumoto, 1960, p. 69), which suggests an age near the Maestrichtian–Campanian boundary. The Maestrichtian age assignment is in agreement with the latest opinion of Frank Anderson as published by Weaver (1944, p. 17). Matsumoto (1960, p. 74) noted that the Gualala group has furnished deformed ammonites comparable with *Didymoceras* cf. D. *hornsbyense* (Whiteaves) and *Diplomoceras?* sp. and suggests that these indicate an "age near the boundary of (the) Campanian–Maestrichtian".

Weaver emphasized that the fossils from the Gualala group were obtained mostly from the middle part of 16,000 feet of strata and that beds higher and lower than the fossiliferous beds might belong to other parts of the Cretaceous system. Durham and Kirk suggested that part of the group might belong to the lower Eocene or Paleocene on the basis of certain fossils collected by them.

30. The Yager formation (Ogle, 1953, p. 16) covers a fairly large area in southwestern Humboldt County and extends into northwestern Mendocino County (Irwin and Tatlock, 1955). The only fossils definitely listed from the formation are the foraminifers *Bathysiphon*, *Silicosigmoilina*, *Cribrostomoides*, and *Clavulina*. The formation probably is younger than the foraminiferal limestone near Barberville in southern Humboldt County mentioned by Irwin (1957, p. 2290), which is presumably of Cenomanian age, as is the limestone near Laytonville in Mendocino County (Irwin, 1957, p. 2290). Some mollusks listed by Anderson (1958, p. 70) are probably from the Yager formation and, if so, indicate that the formation contains beds of Campanian to Maestrichtian age.

31. A limestone mass near Laytonville in north-central Mendocino County was dated by Hans Thalmann (Irwin, 1957, p. 2290), on the basis of Foraminifera, as late Albian to early Cenomanian and as slightly older than the Calera limestone member of the Franciscan formation.

32. Beds of Hauterivian age occur near the Clements ranch in the valley of Redding Creek, Trinity County. They contain many marine mollusks (CAS loc. 1691) (Anderson, 1938b, p. 111, 116–118, 200, 203) that occur elsewhere west of Ono in western Shasta County in the "Hamlin-Broad" zone of Anderson (CAS locs. 113 and 1665). Associated with the mollusks are plant fossils that Knowlton (*in* Diller, 1908, p. 383) identified with the Shasta flora of Early Cretaceous age. Elsewhere in central Trinity County are many small outliers of early Cretaceous age, but the exact age of each outlier has not yet been determined.

At Big Bar on the Trinity River and at Rattlesnake Creek, 25 miles south of Big Bar, plant fossils have been found that Knowlton (*in* Diller, 1908, p. 379–383) considered of Jurassic age. However, in the same beds with the plants at Big Bar was found 4 feet of sandstone containing *Buchia crassicollis* (Keyserling) of Valanginian age (Diller, 1908, p. 381). Fresh-water mollusks found both below and above the *Buchia*-bearing sandstone are presumably also of Valanginian age.

33. The fossils listed by Weaver (1949, p. 44–45) from the Upper Cretaceous beds (Chico formation of Weaver) of Solano County south of Vacaville indicate ages ranging from Turonian to late Campanian if the fossils are correctly identified. Some of the associations of species seem rather unlikely, but the ages indicated are probably represented by sediments, judging by the microfaunal studies of Kirby and Goudkoff and by the ammonites that have been found in the Cretaceous beds to the north and south. Also, the basal beds in the section exposed in Putah Creek (Weaver, 1949, p. 42) have furnished the Turonian ammonite *Romaniceras* (UC B-2040), and the

Campanian ammonite *Canadoceras* has been recorded near Benicia (Gabb, 1869, p. 137, Pl. 23, figs. 15a, b; Matsumoto, 1960, p. 73).

34. The fossils listed by Weaver (1949, p. 38) from his undifferentiated Knoxville and Horsetown (?) formations in Solano and Napa counties are all of Valanginian age, as shown by the presence of *Buchia crassicollis* (Keyserling) and its varieties at most localities, and by *Kilianella crassiplicata* (Stanton) at three localities. The listing of *Glycymeris pacificus* (Anderson) must represent a misidentification as the species is not known below the Cenomanian and does not occur with *Buchia*. A Valanginian age assignment for the fossils listed does not mean, however, that all the 11,000 to 13,000 feet of beds assigned by Weaver (1949, pp. 24–36) to the Knoxville and Horsetown formations is of Valanginian age.

35. The Late Cretaceous formations on the west side of the Sacramento Valley (Kirby, 1943) have furnished a few fossils that permit approximate correlations with the European stages. The "Antelope" shale of Taliaferro contains the Cenomanian ammonites *Turrilites*, *Calycoceras* cf. *sloliczkaia* Collignon, and *Euomphaloceras* and also reworked Albian fossils (David Jones, written communication dated January 19, 1959). The Venado formation is dated as Turonian because at Putah Creek its lower part has furnished the ammonite *Romaniceras*; in the Lodoga quadrangle its basal sandstone has furnished *Inoceramus* cf. *I. labiatus* (Schlotheim); and it contains also a gastropod-pelecypod assemblage that has many species in common with Member I at Redding. The overlying Yolo formation contains the late Turonian ammonite *Subprionocyclus*. The Sites formation contains a microfauna identical with that in the underlying Yolo formation and with Members II, III, and the lower part of Member IV of the Redding district (Goudkoff, 1945, p. 993, 1006). These members contain ammonites of middle to late Turonian age.

The Funks formation is correlated with the Coniacian because it contains the ammonites *Peroniceras* and *Prionocycloceros* (Matsumoto, 1960, p. 33). Furthermore it contains the same microfossils as occur in the Redding area in the upper part of Member IV (Popenoe, 1943b, p. 309–311), which member likewise contains the Coniacian ammonites *Peroniceras* and *Prionocycloceras*. The Guinda formation is correlated with the Santonian partly because of its stratigraphic position and partly because it contains microfossils that some paleontologists consider of Santonian age.

The Forbes formation has furnished a megafauna of unquestioned Campanian age including in particular *Metaplacenticeras*, *Canadoceras*, and *Inoceramus schmidti* Michael. Of these *Metaplacenticeras* has been found about 7 miles northwest of Winters in Yolo County. *Canadoceras* associated with *Patagiosites*, *Anapachydiscus*, and *Inoceramus schmidti* Michael have been found in the Forbes formation at Sand Creek about 10 miles southwest of Arbuckle, Colusa County (CAS loc. 25730). These fossils have been studied by Matsumoto (1960, p. 33, 40) who concludes that they represent the middle and upper Campanian, above the beds characterized by *Submortoniceras*. He notes, however, that even younger beds, probably lower Maestrichtian, characterized by *Baculites rex* Anderson, are present locally in Yolo and Solano counties (Matsumoto, 1960, p. 40). Whether these younger beds should be included in the Forbes formation or in some unnamed formation is not known.

36. Küpper (1956, pp. 40–41) has identified Foraminifera of late Cenomanian age in three shale samples obtained from the "Antelope" shale of Taliaferro from 1650 to 2820 feet below the base of the Venado formation in Colusa and Glenn counties. He notes that the faunule is identical with that in the Calera limestone member of the Franciscan formation at the type locality of the member on Rockaway Beach, San Mateo County, and is younger than that in the Calera limestone member near New Almaden, Santa Clara County (Küpper, 1955) to which he assigns an early Cenomanian age. Irwin (1957, p. 2290) cites Hans Thalmann as an authority that the Calera limestone member near New Almaden, as well as a limestone mass near Laytonville, Mendocino County, are of late Albian to early Cenomanian age and are slightly older than the Calera limestone member at its type locality.

37. Along the west side of the Sacramento Valley between Corning and Vacaville the Lower Cretaceous beds above the Valanginian *Buchia*-bearing beds have furnished few fossils. This condition contrasts greatly with that near Ono in western Shasta County from which area have been obtained most of the Early Cretaceous fossils described by Anderson (1938b). A few collections in the U. S. Geological Survey show that beds ranging in age from late Hauterivian to late Albian are present in western Tehama County from Paskenta northward. Farther south fossils become even less common

in the beds in question. Stanton reports (note book, September 13, 1900) finding a specimen of *Mortoniceras* of late Albian age 1½ miles west of Fruto in Glenn County. David Jones (Fossil Report dated February 10, 1959) mentions the presence of Albian ammonites reworked into beds of Cenomanian age near Fruto. From Grapevine Creek in the Lodoga quadrangle have been obtained *Douvilleiceras* and *Inoceramus* cf. *I. anglicus* Woods of Albian age (David Jones fossil report dated June 9, 1959). The collections at Stanford University contain a specimen of *Mortoniceras* from the Putah Creek area in Solano County. The Aptian ammonite *Parahoplites dallasi* Anderson was found at Fredericks Place, Little Valley, 6 miles northwest of Wilbur Springs, Colusa County (CAS loc. 3351).

38. The Upper Cretaceous near Ono in western Shasta County has furnished the Cenomanian ammonites *Desmoceras* (*Pseudouhligella*) *barryae* Anderson, *Eogunnarites* sp., *Calycoceras* cf. *C. newboldi* (Kossmat), and the Turonian ammonites *Romaniceras*, *Plesiovascoceras*, *Subprionocyclus*, *Collingoniceras*, and *Kanabiceras*. (*See* Matsumoto, 1960, p. 25.) The Coniacian has not been recognized and may be absent.

39. The Ono formation in western Shasta County includes ammonites of late Hauterivian to late Albian age whose stratigraphic ranges locally have been determined by Murphy (1956, p. 2098–2119) by methodical collecting and thorough stratigraphic work. On the basis of his studies he has established a number of ammonite zones whose positions and limits are much more certain than the fossil zones published earlier by Anderson (1938b, Table 2, opposite p. 44, 63–69).

40. Specimens of the Turonian ammonite *Collignoniceras* cf. *C. woollgari* (Mantell) were collected from the south side of Clear Creek, Shasta County, half a mile south of the site of old Horsetown (UCLA coll.)

41. The Early Cretceous beds at Horsetown according to Murphy (1956, p. 2100, 2118, 2110) are only a few hundred feet thick and include only the zones of *Leconteites lecontei*, *Beudanticeras* (*Brewericeras*) *hulense*, and *Oxytropidoceras packardi*.

42. The Campanian ammonite *Metaplacenticeras* has been found at the base of an agglomerate consisting of boulders derived from the Jurassic Logtown Ridge formation about 2 miles southeast of Milton in sec. 24, T. 1 N., R. 10 E., Valley Springs quadrangle, Calaveras County (UC loc. B-5578) (Oral communication from J. W. Durham, July 1959).

43. The Cretaceous at Folsom consists of about 100 feet of medium-grained limonitic sandstone interbedded with siltstone and resting on an irregular surface of granodiorite. A collection from the north side of the American River, a quarter of a mile southwest of the bridge at Folsom, yielded a fauna of 19 species that were identified by Alexander Clark (unpublished report to the Shell Oil Company) as follows:

Acila demissa Finlay
Aphrodina varians (Gabb)
Crassatella tuscana (Gabb)
Cymbophora ashburnerii (Gabb)
C. gabbiana (Anderson)
Exogyra parasitica Gabb
Glycymeris veatchii (Gabb)
Inoceramus whitneyi Gabb
Pedalion excavata ? (White)
Tellina ashburnerii Gabb
Trigonia cf. *T. evansana* Meek
Gyrodes expansa Gabb
Margarites sp. indet.
Oligoptycha obliqua (Gabb)
Volutoderma averillii (Gabb)
Ammonite sp. B.
Baculites chicoensis Trask
Dentalium cooperi Gabb

These species, if correctly identified, suggest a Campanian age, approximately that of *Submortoniceras chicoensis* (Trask), although that species has not been reported at Folsom.

From the Folsom area Matsumoto (1960, p. 21) records *Baculites inornatus* Meek, *B*, cf. *B. occidentalis* Meek, and *Inoceramus* cf. *I. subundatus* Meek. These suggest a Campanian age somewhat younger than that of *Submortoniceras chicoensis* (Trask).

44. Studies of the Cretaceous microfossils from the Marysville area by Kirby (1943, p. 299–302) and Goudkoff (1945, figs. 7a, 14, 16c, 16d) indicate that only foraminiferal zones F-1 and E′ are present. These probably represent only a small part of the Campanian stage. Megafossils found in the upper part of the Cretaceous sequence include *Pachydiscus* sp. juv. cf. *P. egertoni* (Forbes) and *Baculites* cf. *B. inornatus* Meek. These indicate an age near the Campanian–Maestrichtian boundary (Matsumoto, 1960, p. 21).

45. A statement concerning the Cretaceous beds on Chico Creek by LouElla Saul of the University of California at Los Angeles (written communication dated July 30, 1959) is as follows:

"The lowest 700 feet of beds at Chico Creek contain a molluscan fauna similar to that of Members IV and V in the Redding area (Popenoe, 1943 [b], p. 312). The probable late Coniacian age of this part of the section is based upon the presence of *Baculites schencki* Matsumoto (1959 [a], p. 113–118) from 600–700 feet above the base of the Chico Creek section. *B. schencki* Matsumoto also occurs in Members IV and V near Redding.

"Above the lower 700 feet, the succeeding 1,000 feet of beds on Chico Creek contain an assemblage in part similar to that of Member V near Redding. The ammonites from this 1000 feet were identified by Matsumoto and were considered by him to be indicative of Santonian age. They include *Bostrychoceras* aff. *B. otsuki* var. *multicostatum* Yabe (occuring 1,200 feet above the base of the section), *Hauericeras angustum* Yabe (ranging from 1,350 to 1,750 feet above the base of the section), and *Baculites capensis* Woods (Matsumoto, 1959[a], p. 122) (ranging from 1,600 to 1,750 feet above the base of the section).

"Above follows 1,900 feet of beds characterized by *Submortoniceras chicoensis* (Trask), but containing also *Baculites chicoensis* Trask, *Canadoceras* spp., *Turritella chicoensis* Gabb, and many other gastropods and pelecypods that are diagnostic of the *Turritella chicoensis* zone of Popenoe 1942, p. 183). As *Canadoceras* and *Submortoniceras* have not been found earlier or later than the Campanian, these 1,900 feet of beds are considered definitely of Campanian age.

"The highest 400 feet of Cretaceous beds exposed at Chico Creek have yielded fossils (CAS 28172; CIT 1183; UCLA 3648) only in a few beds situated about 100 feet above the highest known occurrence of *Submortoniceras*. The fossils present include the ammonites *Canadoceras newberryanum* (Meek) and *Zelandites* cf. *Z. kaiparaensis* Marshall and the pelecypod *Inoceramus subundatus* Meek which association is considered by Matsumoto to indicate a middle Campanian age. The upper 300 feet of the Chico formation may have furnished the specimen of *Metaplacenticeras pacificum* (Smith) at Harvard University which has an attached label bearing the words "Chico Creek". If this occurrence is valid, it is the only specimen of the genus from Chico Creek."

46. In the Redding area (Popenoe, 1943b) Member I is dated as Turonian by the presence of the ammonite *Tragodesmoceras* and the pelecypod *Inoceramus hobetsensis* Hagao and Matsumoto. Members II and III and the lower 200 feet of Member IV are dated as middle to late Turonian by the presence of the ammonites *Romaniceras*, *Subprionocyclus*, *Eucalycoceras*, and *Mesopuzosia*. Most of Member IV is dated as Coniacian by the presence of the ammonites *Peroniceras*, *Prionocycloceras Hauericeras*, and *Texanites*. Member V and lower part of Member VI are assigned by Matsumoto (1960, p. 12) to the Santonian on the basis of the occurrence of certain species of *Baculites* and *Inoceramus*. The presence of *Pseudoschloenbachia* in the highest part of Member V and of *Inoceramus orientalis ambiguus* Nagao and Matsumoto in the lower part of Member VI indicates that those parts are not older than the late Santonian. A Santonian age for Member VI is indicated, also, by microfossils (personal communication from paleontologists of the Humble Oil Company, November 1957). Some evidence that none of Member VI is younger than Santonian is furnished by some fragmentary baculites similar to *B. capensis* Woods found near the top of the member in the valley of South Cow Creek.

47. The following notes have been prepared by David Jones (August 12, 1959).

"Cretaceous rocks in the Yreka-Hornbrook area, Siskiyou County, California, consist of about 5000 feet of conglomerate, sandstone, and siltstone (Peck *et al.*, 1956; Anderson, 1958; Jones, 1959, p. 1726). Late Turonian fossils, including *Subprionocyclus neptuni* (Geinitz) and *Inoceramus klamathensis* Anderson, occur within several hundred feet of the base. No early or middle Turonian fossils are known. An early Coniacian fauna, including *Prionocycloceras crenulatum* (Anderson), *Desmophyllites* sp., and *Kossmaticeras* sp., occurs about 100 feet higher. A late Campanian fauna characterized by *Metaplacenticeras*, several pachydiscid species, a large species of *Inoceramus*, and *Desmophyllites diphylloides* (Forbes) occurs in a sequence of sandstone and siltstone about 500 feet higher. No late Coniacian to middle Campanian fossils have been found, and possibly part of this interval is represented by an unconformity about 750 feet above the base of the Cretaceous sequence."

48. The following notes have been prepared by David Jones (Aug. 12, 1959).

"Cenomanian rocks are present in the vicinity of Jacksonville and Dark Hollow, Jackson County, Oregon (Jones, 1960). A well-preserved specimen of *Mantelliceras* was found in a sandstone quarry about 1 mile northwest of the center of Jacksonville in the SW¼ sec. 29, T. 37 S., R. 2 W. A fragment of *Acompsoceras?* associated with *Periplomya? oregonensis* Gabb and *Meekia* sp. (USGS Mes. loc. 26251) was found in the NE corner of sec. 11, T. 38 S., R. 3 W. *Desmoceras* (*Pseudouhligella*) *barryae* (Anderson) occurs in the SE¼NE¼ sec. 30, T. 37 S., R. 2 W. (USGS Mes. Loc. 17846), and in Dark Hollow in the SW¼NE¼SW¼ of sec. 13, T. 18 S., R. 2 W. (USGS Mes. loc M116). Other Cenomanian fossils from Dark Hollow are *Calycoceras* sp., *Anagaudryceras* cf. *A. sacya* (Forbes), and *Glycymeris* cf. *G. pacificus* (Anderson).

"Another possible occurrence of rocks of Cenomanian age is on Grave Creek, 10 miles above Placer (USGS Mes. loc. 26280) where an acanthoceratid ammonite similar to *Ammonites turneri* White (not Sowerby) occurs.

"Rocks of Turonian age are widespread in Jackson County and include some beds that are older than any known from the Yreka-Hornbrook area. Lower Turonian fossils, including *Kanabiceras* sp., *Mesopuzosia* sp., and *Inoceramus labiatus*, occur at the southern entrance to Dark Hollow in the

SE¼SW¼ sec. 13, T. 38 S., R. 2 W. Middle and late Turonian fossils, including *Collignoniceras bakeri* (Anderson), *C. branneri* (Anderson), and several species of *Subprionocyclus*, occur at the Fitch Ranch in the Southwest corner of plot 49, T. 38 S., R. 1 E., and at the '49' Mine at the center at sec. 21, T. 38 S., R. 1 W. Early Turonian fossils, including *Tragodesmoceras ashlandium* (Anderson) and *Inoceramus labiatus*, occur near the railroad overpass on the north side of Ashland in sec. 5, T. 38 S., R. 1 E.

"Sandstone of probable early to middle Turonian age crops out along Highway 99 southeast of Ashland. This sandstone contains a prolific molluscan fauna characterized by *Pterotrigonia klamathonia* (Anderson) and *Tragodesmoceras ashlandicum* (Anderson).

"Upper Cretaceous beds, probably of Campanian age, occur in Jackson County, notably at the Oregon–California border (sec. 17, T. 41 S., R. 2 E.) and in the southern part of Bear Creek Valley. These beds consist of sandstone and siltstone identical to Member VI of Peck and others (1956). Large fragments of *Inoceramus* were obtained from the road cut 100 feet north of the California–Oregon border, and *Pterotrigonia evansana* (Meek) was obtained from the SW¼NE¼ sec. 5, T. 39 S., R. 2 E. The occurrence of the late Campanian genus *Metaplacenticeras* has been reported by Anderson (1902, p. 50, 79, 80) from the '49' Mine, but this report has not been validated by additional collecting."

49. The following note has been prepared by David Jones (August 12, 1959).

"Sandstone of probable middle Albian age occurs in a small area on Grave Creek about 8 miles above Placer in sec. 31, T. 33 S., R. 5 W., and sec. 6, T. 34 S., R. 5 W., Wimer quadrangle. The Albian fossils include *Lyelliceras*, *Oxytropidoceras?*, and *Cleoniceras?* (Jones, 1960, p. 154)."

50. Cretaceous rocks some hundreds of feet thick crop out in the northwestern part of the Takilma-Waldo area in Josephine County (Shenon, 1933, p. 150–152, Pl. 11; Imlay *et al.*, 1959, p. 2777, 2784). The lower part of the sequence consists of coarse conglomerates and some sandstone, and the upper part consists mostly of sandstone. The sandstone is mostly massive, greenish gray, and weathers into medium to dark brown spheroidal masses. Lithologically it is similar to beds of Hauterivian age elsewhere in southwestern Oregon. The contact of the conglomerate with the underlying Galice formation is exposed at the bridge across the Illinois River east of O'Brien.

At two places this Cretaceous sequence has furnished fossils that indicate a late Hauterivian to Barremian age. One collection (USGS Mes. loc. 3339) from the deep cut draining the Logan mine, about 4 miles north of Waldo, contains *Inoceramus ovatoides* Anderson, *Trigonia* cf. *I. leana* Gabb. *Entolium operculiformis* Gabb, and a fragmentary ammonite suggestive of *Simbirskites*. The other collection (USGS Mes. loc. 2166) made from the Simmons cut 3 miles north of Waldo contains *Shasticrioceras* cf. *S. poniente* Anderson, *Inoceramus ovatoides* Anderson, *Trigonia kayana* Anderson, *Trigonia* cf. *T. leana* Gabb, *Entolium operculiformis* Gabb, *Meekia* sp., *Pleuromya papyracea* Gabb, *Solecurtus* sp., *Nucula* sp., and *Corbula* sp.

Of these fossils, *Inoceramus ovatoides* Anderson in California ranges through the *Hertleinites aguila* zone and the *Shasticrioceras poniente* zone (Murphy, 1956, Fig. 6 on p. 2114) which corresponds to the late Hauterivian and the Barremian stages of Europe. The presence of *Shasticrioceras* cf. *S. poniente* Anderson at one locality suggests a correlation with the *S. poniente* zone in California, although the genus occurs rarely in the *Hertleinites aguila* zone. The presence of these fossils and the absence of the Valanginian *Buchia crassicollis* (Keyserling) from any part of the sequence all indicate an age younger than Valanginian.

51. Several collections of late Campanian to early Maestrichtian age have been obtained near the Oregon coast on the Pistol River and in nearby areas to the north in Curry County. *Inoceramus subundatus* Meek (equals *Inoceramus whitneyi* Gabb) occurs as on Myers Creek in sec. 32 (USGS Mes. loc. 2076) and sec. 26 (USGS Mes. loc. 2163), T. 37 N., R. 14 W. Loc. 2163 also contains pelecypods identified by T. W. Stanton as *Meekia navis* Gabb and *Cymbophora ashburneri* Gabb. About 3 miles above the mouth of the Pistol River (USGS Mes. loc. 2162) was obtained a collection containing *Meekia navis* Gabb, *Cymbophora ashburneri* (*Gabb*), *Mytilus pauperculus* Gabb, and *Cardium* ? sp. On the coast at the mouth of Pistol River was obtained two small inoceramí (USGS Mes. loc. 2123) that probably belong to *I. subundatus* Meek. According to W. P. Popenoe the species of *Meekia* present in these collections is unlike the species in the Moreno formation but identical with that in the *Metaplacenticeras* beds in California.

52. Near Agness, Curry County, the Valanginian is represented by a thin unit of sandstone containing *Buchia crassicollis* (Keyserling) and is overlain almost directly by massive greenish-gray spheroidal-weathering sandstone containing middle Hauterivian ammonites belonging to *Simbirskites*, *Hollisites*, and *Hoplocrioceras*. The absence of lower Hauterivian beds cannot be explained by lack of exposures and probably is a result of faulting, but

the true explanation must await detailed mapping.

53. The Port Orford area, Curry County, contains a fairly thick sequence of beds of Valanginian age that is well exposed along Elk River and the Sixes River and some hundreds of feet of beds of Hauterivian age exposed along the coast south of Port Orford. Exact thicknesses are unknown but probably total several thousand feet. The Valanginian beds are characterized by the pelecypod *Buchia crassicollis* (Keyserling) and at a few places have furnished ammonites. A quarter of a mile below the forks of Elk River (USGS Mes. loc. 2154) have been found the ammonites *Homolsomiles mutabilis* (Stanton), *Thurmanniceras jenkinsi* Anderson, *T. stippi* Anderson, *Sarasinella* n. sp., and *Acanthodiscus* sp. juv. aff. *A. subradiatus* Uhlig. About 500 feet lower on the South Fork of Elk River was obtained *Sarasinella hyatti* Stanton (USGS Mes. loc. 4384). This species also occurs on Bald Mountain near the head of Brush Creek (USGS Mes. locs. 2107, 2136). The presence of beds of early Hauterivian age is based on a specimen of *Olcostephanus* resembling species of that age from Mexico and Europe. This was obtained from exposures along the beach 2 miles south of Port Orford in the NW¼ sec. 15, T. 33 S., R. 15 W.

54. An isolated occurrence of *Buchia crassicollis* (Keyserling) is recorded from 1 mile southwest of Powers, Coos County, about three-quarters of a mile above the mouth of Salmon Creek (USGS Mes. loc. 2141).

55. *Inoceramus subundatus* Meek, *Baculites* sp., and a fragment of a large, fairly smooth, compressed pachydiscid ammonite have been obtained from the South Fork of Dement Creek, near center of south edge of sec. 25, T. 30 S., R. 13 W., Coos County (USGS Mes. loc. 2148). This occurrence indicates the presence of Cretaceous beds of nearly the same age as those near the mouth of Pistol River in Curry County.

Beds of Valanginian to Barremian age cropping out in southwestern Oregon have been assigned by Imlay and others (1959, p. 2782) to the Days Creek formation in the upper part of the Myrtle group. The Days Creek formation includes the Horsetown formation and the Cretaceous part of the Knoxville formation of Diller and Kay (1924) as mapped in the Riddle quadrangle. The Upper Jurassic (Portlandian-Tithonian) beds underlying the Days Creek formation have been assigned to the Riddle formation in the lower part of the Myrtle group (Imlay and others, 1959, p. 2774). The Myrtle group, originally proposed by Louderback (1905, p. 528), corresponds with the Myrtle formation of Diller (1898, p. 1) as exposed in the Myrtle Creek Valley. It does not include any Jurassic rocks older than the Riddle formation or any Upper Cretaceous rocks.

56. A sequence several thousand feet thick of Valanginian and early and middle Hauterivian age crops out along the Foggy Creek road near the head of the South Coquille River, Coos County. The Valanginian and lower Hauterivian beds appear to be overturned to the northwest. The Valanginian consists of about 1000 feet of conglomerate and conglomeratic sandstone and a similar thickness of mudstone and siltstone. *Buchia crassicollis* (Keyserling) occurs throughout and is particularly abundant in the conglomeratic beds. The early Hauterivian is represented by *Wellsia oregonensis* Anderson (USGS Mes. loc. 25213) and *Hannaites riddlensis* (Anderson) (USGS Mes. loc. 25212) in a sequence more than 400 feet thick. Considerably higher stratigraphically, the middle Hauterivian ammonite *Simbirskites* was obtained in association with *Hoplocrioceras* and *Spitidiscus* (USGS Mes. locs. 24449, 25211) from the west side of the Foggy Creek road in the SE¼ NE¼ sec. 8, T. 32 S., R. 10 W. The beds in which these ammonites were found are probably not overturned, but their exact relationship to the lower Hauterivian beds has not been determined. As elsewhere in southwestern Oregon the beds of Hauterivian age consist mostly of soft, massive, greenish-gray sandstone that weathers into brownish spheroidal masses and is poorly exposed except along streams and artificial cuts.

57. A continuous sequence of beds of Valanginian and early Hauterivian age is exposed on the South Umpqua River near Days Creek, Douglas County, and has been described in detail by Imlay and others (1959, pp. 2775, 2782). The Valanginian part of the sequence is at least 376 feet thick and consists of alternating thick units of medium-gray sandy siltstone and somewhat thinner units of dark-greenish-gray, fine-grained sandstone. The siltstone includes some limestone lenses and concretions.

Below these beds is 33 feet of conglomerate in a siltstone matrix whose age is in question. The lower part of this unit locally contains many specimens of *Buchia piochii* (Gabb) and *B. fischeriana* (D'Orbigny) of Portlandian age. Some of these Buchias appear to be

slightly rounded as though they were derived from older beds. At one place, however, on the west side of the river the Buchias form a coquina nearly a foot thick and show no evidence of rounding. This occurrence is good evidence that the lower part of the 33 feet of conglomeratic siltstone is of Portlandian age but does not prove that all the unit is of that age.

The Valanginian age of the 376 feet of sandstone and siltstone above the conglomeratic beds is based on the presence of *Buchia crassicollis* (Keyserling) and *Olcostephanus* cf. *O. jeannoti* (D'Orbigny). *B. crassicollis* ranges from 46 to 376 feet, and *Olcostephanus* from 108 to 291 feet above the conglomerate. The 46 feet of beds above the conglomerate is assigned to the Valanginian on a lithologic basis.

The Hauterivian part of the sequence that was measured on the South Umpqua River is 433 feet thick, is terminated at its top by a fault, and includes ammonites of only early Hauterivian age. It consists of thick alternating units of fine-grained sandstone and sandy siltstone that are commonly massive to medium-bedded, are dark greenish gray, and weather to dark-brown, spheroidal masses. These units contain many small fossiliferous limestone concretions. All beds weather easily and are poorly exposed except along the bed and banks of the river. The concretions have furnished many pelecypods and ammonites but contain, also, some gastropods and crustaceans. The ammonite *Wellsia oregonensis* (Anderson) has been collected from 58 to 243 feet above the top of the Valanginian beds bearing *Buchia crassicollis* (Keyserling). *W. packardi* (Anderson) has been collected from 253 and 413 feet above the Valanginian beds. Other ammonites present include *Hannaites riddlensis* (Anderson), *Phylloceras umpquanum* Anderson, and *Crioceratites* cf. *C. latus* (Gabb).

Sequences of Valanginian-Hauterivian age similar lithologically and apparently in thickness to that on the South Umpqua River near Days Creek are exposed in the bed of Cow Creek at the town of Riddle and in Myrtle Creek east of the town of Myrtle but are difficult to measure because of folding and faulting. In the Dutchman Butte quadrangle the Hauterivian beds have not been identified and are probably lacking, but Valanginian beds containing numerous characteristic plump specimens of *Buchia* are widespread.

Part of the sequence exposed in the bed of Cow Creek above the bridge at Riddle is of middle Hauterivian age as shown by the presence of *Simbirskites* aff. *S. elatus* (Trautschold) and *Hollisites* n. sp. obtained from a bed of gray sandstone 15 feet thick exposed at the upper end of the bridge on the south bank of the creek (USGS Mes. loc. 1251).

58. The Myrtle formation as mapped by Diller (1898) covers extensive areas in the southern part of the Roseburg quadrangle. From this formation Diller and his assistants collected many fossils that were identified by T. W. Stanton as *Buchia piochii* (Gabb), *B. crassicollis* (Keyserling), *Pecten operculiformis* Gabb, and *Trigonia aequicostata* Gabb. *B. piochii* (Gabb) is now considered of middle to late Portlandian age, and *B. crassicollis* (Keyserling) of Valanginian age. The specimen that was illustrated by Diller as *Trigonia aequicostata* Gabb was designated by Anderson as the type of his new species *Trigonia kayana*. The type actually was obtained near Ono, California, and probably from the *Shasticrioceras ponienti* zone of Barremian age, but in Oregon the species occurs throughout Hauterivian beds as well as in Barremian beds.

Recent investigations (Imlay and others, 1959) of the various fossil localities in the Roseburg quadrangle found by Diller and his associates have shown that beds of Portlandian, Valanginian, and Hauterivian ages are represented in the valley of Myrtle Creek and its tributaries and that beds of Portlandian and Valanginian ages are represented in the southwest corner of the Roseburg quarangle along the upper parts of Willis, Rice, and Kent creeks. No fossils were found, however, in the area mapped by Diller as Myrtle formation east and southeast of Roseburg, or along the south Umpqua River, in spite of the fact that specimens of *Buchia crassicollis* (Keyserling) were obtained by Diller (1907, p. 416) in these areas and are now in the collections of the U. S. Geological Survey (USGS Mes. locs. 1685, 2022, 3942, 3943, 4407). The presence of such fossils is peculiar because most of the rocks within the areas in question are identical lithologically with the Dothan formation rather than with the Myrtle formation as mapped by Diller on Myrtle Creek.

Possibly bearing on the problem is the occurrence within these areas of the Whitsett limestone lentils which are associated with the beds that resemble the Dothan formation but which were included by Diller in the Myrtle formation. From one of these lentils on Roberts Creek southeast of Roseburg in secs. 14 and 15, T. 28 S., R. 5 W., Diller obtained some fossils identified by Stanton (Diller, 1898, p. 2) as

Opis californica Stanton and *Hoplites* cf. *H. dilleri* Stanton (USGS Mes. loc. 2026). The species *H. delleri* Stanton is now placed in the genus *Kossmatia* of middle Portlandian age. The ammonite from Locality 2026 does not belong to *Kossmatia*, however, but rather resembles immature specimens of the middle Portlandian genus *Durangites* which is common in Mexico and Cuba and has been recorded by Anderson (1945, p. 983) from California. The presence of such an ammonite indicates, therefore, that at least one of *Diller's* Whitsett limestone lentils is of middle Portlandian age; if true, this explains why the underlying rocks resemble the Dothan formation rather than the typical Myrtle. This dating implies that the collections of *Buchia crassicollis* (Keyserling) obtained by Diller's party within the area containing the Whitsett limestone lentils were not found in place or may have been obtained from outliers or slumped masses.

The problem requires more field work, however, considering that Thalmann (1943, p. 1827) found microfossils of Cenomanian or Turonian age in one of the Whitsett limestone lentils. This lentil exposed near the South Fork of Deer Creek in the NE¼ sec. 31, T. 27 S., R. 4 W., contains certain species of Foraminifera that have been variously placed in *Globotrunca* or *Rotalipora* of Cenomanian to Turonian age (Imlay and others, 1959, p. 2779). The specimens from this lentil have been examined, also, by Weldon Rau, Merle Israelsky, and Ruth Todd, who agree with Thalmann's age determination. It appears, therefore, that the limestone lentil on Deer Creek is much younger than the limestone lentil on Robert Creek.

59. Beds of Albian to possibly Cenomanian age crop out rather widely in the southeastern part of the Mitchell quadrangle near the town of Mitchell. The sequence is 2000 feet or more in thickness and consists mostly of dark-gray shale. Some sandstone is interbedded throughout and becomes more common upward. The basal beds are either sandstone or conglomerate that rests on greenstone and altered sedimentary rocks. Near the base of the sequence in the south-central part of sec. 3, T. 11 S., R. 22 E., were obtained *Leconteites lecontei* (Anderson), *L. modestum* (Anderson), *Pusozigella perrinsmithi* (Anderson), *P. rogersi* (Hall and Ambrose), and *Douvilleiceras* sp. These fossils occur in California in the zone of *Leconteites lecontei* (Murphy, 1956, p. 2114, 2115, 2118), dated by the presence of *Douvilleiceras* as early Albian, or the early middle Albian. Near the middle of the sequence was found the Late Albian ammonite *Mortoniceras*, which is represented in the collections at Stanford University. Near the top of the sequence in the SE¼ NW¼ sec. 27, T. 12 S., R. 20 E, was found the late Albian ammonite *Desmoceras* (*Pseudouhligella*) *dawsoni* Whiteaves (Fossil report from David L. Jones dated November 1959). The highest beds have furnished few fossils and possibly represent the basal Upper Cretaceous which has been identified faunally at many localities in central Oregon east and south of the Mitchell area.

60. Upper Cretaceous gray shale and sandstone ranging in thickness from several hundred feet to about 2000 feet crop out at a number of localities along, or near, the northern front of the Ochoco Mountains in central Oregon and at one locality within the mountains. The main exposures are about 1 to 4 square miles in area and are located as follows:

(1) South of Antone between Rock Creek and Spanish Gulch in secs. 12 and 13 and SE¼ sec. 11, T. 13 S., R. 24 E., Wheeler County

(2) West of Dayville near Battle Creek in SW¼ sec. 3, SE¼ sec. 4, and sec. 9, T. 13 S., R. 26 E., Grant County

(3) North slope of Aldrich Mountain near road in sec. 35, and between Flat and Bridge creeks in SW¼ sec. 25, T. 13 S., R 27 E., Grant County

(4) Northeast of John Day in SW¼SW¼ sec. 10 and in sec. 15, T. 12 S., R. 33 E., Grant County

(5) Andrew Bernard Ranch on Beaver Creek north and northeast of Suplee in a band about half a mile wide trending northeast from sec. 33 to sec. 1, T. 17 S., R. 25 E., Wheeler County

(6) North of Deer Creek extending northeast from the south-central part of sec. 3, T. 16 S., R. 27 E., to the west-central part of sec. 36, T. 15 S., R. 27 E., Grant Co.

The beds at these localities have furnished a fairly large molluscan fauna of earliest Late Cretaceous age as illustrated by collections (USGS Mes. locs. 26279 and 26708) from the Andrew Bernard Ranch on Beaver Creek which are listed as follows:

Turrilites oregonensis Gabb (equals *T. costatus* Lamarck)
Desmoceras (*Pseudouhligella*) *japonicum* Yabe
Exogyra parasitica Gabb
Periplomya? *oregonensis* Gabb?
Linearia multicosta Gabb
Tenea cf *T. inflata* Gabb?
Calva cf. *C. varians* (Gabb)
Trigonia evansana var *oregona* Packard

T. leana Gabb
T. jacksonensis Packard
Meekia cf. *M. sella* Gabb
Dentalium stramineum Gabb

The beds containing these fossils are dated rather closely by the presence of the subgenus *Pseudouhligella*, which is not known above the Cenomanian (Matsumoto, 1953, p. 252), and by *Turrilites*, which occurs mostly in the Cenomanian and is not known above the lower Turonian.

Elsewhere in central Oregon the ammonites *Desmoceras* (*Pseudouhligella*) and *Turrilites* have been found only on Battle Creek (USGS Mes. loc. 26375), but elements of the pelecypod assemblage have been found at a number of localities. Many of the pelecypods are known from the Medford-Jacksonville area of southwestern Oregon in beds ranging in age from Cenomanian to Turonian, as dated by ammonites.

61. The Cretaceous foraminifer *Globotruncana* (collected by Hollis Hedberg) has been found in the headwaters of the Wynoochee River, about Lat. 47° 30′ N., Long. 123° 32′ W., Grays Harbor County, in the southern part of the Olympic Peninsula (J. L. Harvey, 1959, M. S. Thesis, Univ. Wash.).

62. The Swauk formation of north-central Washington consists of 3500 to 7000 feet of gray sandstone, black shale, and locally some conglomerate. Plants from the formation were studied by F. H. Knowlton (1904, p. 5) who correlated them with the Laramie, Denver, and Fort Union formations of the western interior region and dated them as early Eocene. Later some collections of plants from the Swauk formation were studied by Caroline A. Duror (*see* C. L. Willis, 1950, Thesis, Univ. Wash., p. 88, 89) who reported that 2 species were new and 17 had been found previously in the Fort Union formation. Another collection was studied by R. S. La Motte (*see* C. L. Willis, 1960, Thesis, Univ. Wash., p. 92) who identified 14 species of Paleocene age. La Motte noted that the flora common to the Swauk formation occurs also in rocks exposed in the north Fork of Nooksack River west of the Cascade Mountains in the Van Zandt quadrangle. These rocks are now referred to the Chuckanut formation whose basal beds may be of Cretaceous age. (*See* annotation 66.) By comparison the basal beds of the Swauk formation might also be of latest Cretaceous age. The highest part of the Swauk formation cannot be younger than early Eocene according to F. Alexander (1956, Thesis, Univ. Wash. p. 42) because the formation is overlain unconformably by the Teanaway basalt which is overlain conformably by the Roslyn formation of middle Eocene age.

Marine Cretaceous rocks are not known from the area of outcrop of the Swauk formation. However, about 30 miles west of the westernmost exposures of that formation the presence of a Late Cretaceous baculite was reported by Diller (1893, p. 217), who said that the specimen was obtained by E. W. P. Guye on the Snoqualmie River, 3 miles below the falls in King County. This occurrence was questioned by Weaver (1916, p. 26) who said "Careful areal geological studies have been made in that region and no strata have been found which could be assigned to the Cretaceous. It was undoubtedly derived as a fragment from the glacial drift which in that region heavily veneers the country.

This statement has been confirmed by V. Standish Mallory (written communication of September 30, 1959) from his observations along the Snoqualmie River upstream from the town of Fall City which is about 3 miles below the falls. He says that the rocks in the area consist of volcanic rocks and do not remotely resemble any Cretaceous sedimentary rocks with which he is familiar.

63. The presence of beds of earliest Cretaceous age east of Everett, Washington, in the western foothills of the Northern Cascade Mountains, is based on identifications by J. A. Jeletzky of the Canadian Geological Survey for Wilbert R. Danner. According to Danner (written communication dated October 2, 1957) Jeletzky identified species of *Aucella* (now called *Buchia*) of both latest Jurassic (Tithonian) and earliest Cretaceous (Berriasian or Infra-Valanginian) ages from part of the Nooksack group "cropping out along the western edge of the Cascade Mountain foothills west of the belt of Permian Stillaguamish group rocks."

The Cretaceous Aucellas were identified by Jeletzky as *Aucella* ex gr. *A. volgensis* Lahusen or *Aucella* ex gr. *okensis* Pavlow and identical with species at the base of the Cretaceous in parts of British Columbia.

64. The characteristics, thicknesses, and distribution of the Upper Cretaceous rocks along the northern margin of the San Juan Islands have been discussed by McLellan (1927, p. 118–136 and accompanying geologic maps) who refers the rocks to the Nanaimo group that outcrops more widely in nearby parts of

Vancouver Island. He lists marine Late Cretaceous fossils from Sucia, Waldron, and Skipjack islands and notes that Late Cretaceous plants occur on Orcas Island (Newberry, 1863). Most of the marine fossils listed by McLellan (1927, p. 133–135) are from 700 feet of sandy shale near the base of the Cretaceous sequence on the south side of Sucia Island. These fossils have been described by many paleontologists (Meek, 1861; 1876; White, 1889; Whiteaves, 1879; 1903; and Usher, 1952). The beds containing them have been assigned by Usher (1952, p. 15, 17) to the Cedar District formation and correlated with the upper part of the Campanian stage on the basis of the association of such ammonites as *Hoplitoplacenticeras*, *Pachydiscus*, *Canadoceras*, and *Desmophyllites*. Presumably other formations of the Nanaimo group occur in San Juan Islands, but generally they have not been described in publications. For example, about 3700 feet of Cretaceous rocks exposed on Stuart Island has been correlated lithologically and faunally with the Northumberland and DeCourcy formations that are exposed about 10 miles to the northwest in British Columbia (D. W. Phifer, 1955, Thesis, Univ. Wash.). Fossil evidence for this correlation consists in part of the presence of *Canadoceras newberryanum* (Meek) and *Inoceramus vancouverensis* Shumard in the upper 250 feet of the section on Stuart Island.

65. Valanginian beds have been identified in the San Juan Island group only on Spieden Island and Sentinel Island (McLellan; 1927, p. 113–114). On Spieden Island they are more than 2000 feet thick and consists mostly of sandy conglomerate. From some sandstone and shale along the north shore of the Island McLellan (1927, p. 114–118) collected many mollusks including a few specimens of *Homolsomiles stantoni* (McLellan) (1927, p. 115; Imlay, 1956) and numerous specimens of *Buchia crassicollis* (Keyserling).

66. The Chuckanut formation exposed in the western part of Whatcom County consists of arkosic sandstone, sandy shale, locally conglomerate, and some coal beds. Weaver (1937, p. 75–90) notes that the plant fossils studied by Knowlton (*see* Landes, 1902, p. 263–265) and Lesquereux (1859, p. 360–363) have been correlated with the Eocene, but he considers (p. 90) that deposition of the Chuckanut formation "may represent a time interval beginning in the late Cretaceous and continuing into the middle or possibly late Eocene." The possibility that the lower part of the Chuckanut formation is of late Cretaceous age is indicated, also, in a statement by Bradley (1950, p. 1520) that the "conglomerates of the Chuckanut formation, assigned to the Eocene on plant evidence, are indistinguishable from the Cretaceous conglomerates immediately above the Cretaceous faunal horizons" on Vancouver Island and the San Juan Islands. Also, the beds now called Chuckanut formation were considered by McLellan (1927, p. 136) to include continental equivalents of the upper part of the Nanaimo group.

67. The term Nooksack group was proposed by Peter Misch in a letter to Vernon E. Swanson, dated November 15, 1954, for certain Jurassic and Cretaceous rocks exposed in the Nooksack River area north of Mount Baker, Whatcom County, Washington (Misch, 1952). The term was published by McKee *et al.* (1956) in the Paleotectonic Maps of the Jurassic System. Peter Misch notes that the lower 4000 feet of the Nooksack group contains Late Jurassic megafossils, and the upper 1000 feet contains Early Cretaceous fossils of probable Valanginian age, based on identifications by Doctor Jeletzky of the Canadian Geological Survey. The Foraminifera present suggest an age not older than Jurassic (Misch and Mallory, 1956, p. 1775).

The fossils in the U. S. Geological Survey collections confirm these age determinations. *Buchia rugosa* (Fischer) and *B. mosquensis* (Von Buch) of middle Kimmeridgian to early Portlandian age were obtained along Church Mountain Road in the SE¼ sec. 35, T. 40 N., R. 7 E. *Buchia piochii* (Gabb) of Portlandian age was obtained on the right bank of the Left Fork of the Nooksack River 1.1 miles below Bridge Camp bridge in the southwest corner of sec. 35, T. 40 N., R. 7 E. *Buchia crassicollis* (Keyserling) of Valanginian age was obtained 2.1 miles below Bridge Camp bridge in the north-central part of sec. 3, T. 39 N., R. 7 E. A collection made on the lower part of the Skyline Trail southeast of Glacier contains the Valanginian *Buchia crassicollis* (Keyserling) and *Homolsomites stantoni* (McLellan) (Imlay, 1956, p. 1145). In addition to these fossils, some of the specimens of *Homolsomites stantoni* (McLellan) studied by McLellan (1927, p. 115) were obtained about 2 miles east of the village of Glacier in sec. 5, T. 39 N., R. 7 E. A University of Washington collection (UWA 538) made 3 miles east of Glacier contains this ammonite in association with *Olcostephanus*.

68. The name Pasayten formation was de-

fined by Smith and Calkins (1904, p. 28–30) for Cretaceous rocks east of the Skagit River, Whatcom County, Washington. The evidence for a Cretaceous age consisted of a fern identified by F. H. Knowlton as *Dryopteris oerstedi* Heer and a gastropod *Actaeonella* identified by T. W. Stanton. These fossils have not been located for re-examination. The genus *Actaeonella* has been found in Europe in strata ranging from Barremian to Maestrichtian in age. In Texas it has been found in rocks as old as Albian. In the West Coast States it has not yet been reported from rocks older than Late Cretaceous.

Other evidence concerning the age of the Pasayten formation has been obtained from the Princeton area in British Colombia (Rice, 1947, p. 23) where beds referred to the Pasayten group by Rice have furnished many plants including the fern identified by Knowlton. These plants have been identified by W. A. Bell of the Canadian Survey as "very late lower Cretaceous age, equivalent to the Albian of Europe." This age determination is confirmed by Roland W. Brown of the U. S. Geological Survey who says the same flora occurs in the middle Albian Cheyenne sandstone in Kansas.

69. The Dewdney Creek formation has been mapped by Peter Misch (letter to Vernon E. Swanson dated November 27, 1954) in easternmost Whatcom County, Washington, as an extension of the Dewdney Creek group of British Columbia. The formation in Washington was listed on the Paleotectonic Maps of the Jurassic System by McKee *et al.* (1956) as partly of Jurassic age. In the Princeton area of British Columbia (Rice, 1947, p. 18–19) the upper 7200 feet of the Dewdney Creek group has furnished fossils definitely of Early Cretaceous age including *Shasticrioceras*? sp. and *Inoceramus colonicus* Anderson (synonym of *I. ovatoides* Anderson). These fossils in California occur only in the zones of *Hertleinites aquila* and *Shasticrioceras poniente* which are correlated with the late Hauterivian and the Barremian stages on the basis of ammonites.

Both *Shasticrioceras* and *Inoceramus ovatoides* Anderson (equals *I. colonicus* Anderson) have been found elsewhere on the West Coast near Ono, California, and in the Takilma-Waldo area, southwest Oregon. Nearby in British Columbia they have been found in the Princeton area (Rice, 1947, p. 18, 19). Near Ono, California, they range through the *Hertleinites aquila* zone and the *Shasticrioceras poniente* zone (Murphy, 1956, Fig. 6 on p. 2114) which corresponds to the late Hoterivian and the Barremian stages. As *Shasticrioceras* is uncommon in the *Hertleinites aquila* zone, most of the occurrence of this genus in the Methow Valley are apt to be of Barremian age.

70. The Pipestone Canyon formation rests on granite, gneiss, or on Barksdale's Newby formation but has not been found in contact with the Midnight Peak formation. It has furnished plant fossils at one place in the east-central part of sec. 22, T. 34 N., R. 22 E., above 5 miles north of Twisp. These plants were identified by J. Stewart Lowther as *Paratoxodium* sp. and *Nymphaeites* aff. *N. angulatus* (Newberry) (D. J. Ryason, 1959, M. S. Thesis, Univ. Wash., p. 17–20). Of these plants *Paratoxodium* is known elsewhere by only a single species from the Upper Cretaceous Prince Creek formation of northern Alaska (Arnold and Lowther, 1955), and *Nymphaeites angulatus* (Newberry) has been reported from beds of Late Cretaceous to Eocene Age (Bell, 1949, p. 34, 66).

71. Barksdale's Midnight Peak formation, consisting mostly of 8000 feet of andesitic tuffs, breccias, and flows, has not furnished any fossils. It is considered to be Cretaceous because it grades downward into the Winthrop sandstone (Russell, 1900; Barksdale, 1948, p. 173, 174).

72. A Late Cretaceous age for the 2500 feet of Winthrop sandstone is based on two plant collections identified by Roland W. Brown (Barksdale, 1948, p. 172, 173). One was obtained 6½ miles northwest of Winthrop on the Harts Pass road. The other was obtained 2 miles north of B. M. 2806 on Twisp River. The preservation of the material does not permit a correlation with any particular European stage of the Upper Cretaceous. As the Winthrop sandstone is reported to rest conformably on the Virginian Ridge formation, it may be only slightly younger.

73. The Virginian Ridge formation (Barksdale, 1948, p. 169–171) is reported to be 10,000 to 12,000 feet thick, to consist mostly of black to dark-greenish siltstone, but to include a basal unit of greenish-black sandstone and conglomerate ranging from a few hundred to more than 1000 feet thick. From near the top of the basal conglomerate on a hill east of Patterson Lake, 3 miles S. 65° W. of Winthrop, Barksdale obtained fossils identified by Ralph Stewart and W. P. Popenoe. These include in particular *Trigonia* cf. *T. evansana* Meek, *T.* cf. *T. leana* Gabb, *Turritella* sp., and *Cucullaea* cf. *ponderosa* Whitfield. The Trigonias indicate a late Albian to Turonian age. As they were

found low in the formation, most of the formation is probably somewhat younger.

The same species of *Trigonia* were obtained by Donald L. Maurer, graduate student at the University of Washington, in sandstone beds in the lower conglomeratic part of the Virginian Ridge formation in Alpine Valley 4–5 miles northwest of Winthrop. In addition two specimens of the ammonite *Beudanticeras* (*Brewericeras*) *haydeni* (Gabb) were obtained from surface rubble of the conglomeratic beds, and a third specimen of the same species was turned up by plowing in a nearby field. These ammonites would date the lower part of the formation as middle to late Albian if they had been found in place. According to Julian Barksdale (oral communication of July 20, 1959) the Trigonias and other pelecypods occur in a sandstone matrix and show no evidence of having been derived from older rocks. Also, the matrix associated with the ammonites is lithologically similar to that of the Virginian Ridge formation and is unlike that of the older Newby formation. He is convinced, therefore, that the fossils found in the basal part of the Virginian Ridge formation were not derived from older beds.

According to Julian Barksdale (written communication dated March 31, 1960) the Virginian Ridge formation in the Methow area rests unconformably on the Newby formation, or on an arkosic sandstone that overlies the Newby formation and that is probably correlative with the Jackass Mountain formation in British Columbia. The Virginian Ridge formation thins northwestward toward the Slate Peak lookout in the Harts Pass area where it has furnished well-preserved specimens of *Actaeonella* (USGS Mes. loc. 26264). The underlying arkosic sandstone thickens toward the Harts Pass area where it has furnished some ammonites (Barksdale, 1948, p. 170) a few hundred feet east of the crest of Harts Pass. These ammonites were identified by S. W. Muller as belonging to the genera *Puzosia* and *Hamites* whose association indicates an Albian to Cenomanian age.

74. Both Albian and Barremian mollusks have been obtained in the Methow Valley a few miles north of Winthrop, based on collections at the University of Washington. Evidence for an Albian age consists of four ammonites belonging to the genus *Beudanticeras* (*Brewericeras*). Three of these ammonites were found on the surface of the basal conglomeratic beds of Virginian Ridge formation, as discussed under Annotation 73. The fourth ammonite, identified by Imlay as *Beudanticeras* (*Brewericeras*) cf. *B. haydeni* (Gabb), was found in place in the Newby formation in the Buck Mountain area in the NE¼ SW¼ sec. 33, T. 36 N., R. 21 E., Doe Mountain quadrangle (University of Washington loc.UWA-539). Its stratigraphic occurrence, according to D. L. Maurer, is about 600 feet above the base of 1400 feet of dark siltstone at the top of the Newby formation.

Below the 1400 feet of dark siltstone in the Buck Mountain area, D. L. Maurer (M. S. Thesis, Univ. Wash., p. 29–30) measured about 7900 feet of conglomerate, sandstone, siltstone, and shale that are in fault contact on the east with metamorphic and igneous rocks in the Okanogan Mountains. From the sedimentary beds he obtained the ammonite *Shasticrioceras* and the pelecypod *Inoceramus ovatoides* Anderson at several levels from 2500 to 6100 feet below the occurrence of *Beudanticeras* (*Brewericeras*) cf. B. *haydeni* (Gabb) at University of Washington loc.UWA-539. Most of the collections of these mollusks were made about 7 miles north of Winthrop in secs. 21 and 28, T 36 N., R. 21 E., but one was made in sec. 10, T. 35 N., R. 21 E. In addition the collections at Stanford University contain the same fossils from 5.3 miles north of Winthrop in sec. 13, T. 35 N., 21 E.

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Short Notes

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SUBDIVISION OF THE QUATERNARY ALLUVIUM EAST OF THE FRONT RANGE NEAR DENVER, COLORADO

BY GLENN R. SCOTT

A detailed subdivision of Quaternary alluvium near Denver, Colorado (Fig. 1), is based on studies by Hunt (1954), Malde (1955), Van Horn (1958), and Scott. This subdivision includes five hitherto unrecognized alluvial formations (Table 1), each of which is widely distributed in the Denver area. The three older alluvial deposits were laid down as broad veneers on pediments; the two younger deposits were laid down as terraces in valleys entrenched into the pediments. Recognition and differentiation of the formations are based primarily on superposition, physiographic position, and ancient soils; in addition, fossil mammals and mollusks, absolute age by radiocarbon analysis, and synchronous beds such as volcanic ash are used wherever available. Lithologic differences between formations generally are subtle, but they are real, and their recognition and application are beginning to result in a better understanding of the geomorphic development of the High Plains area east of the Front Range near Denver.

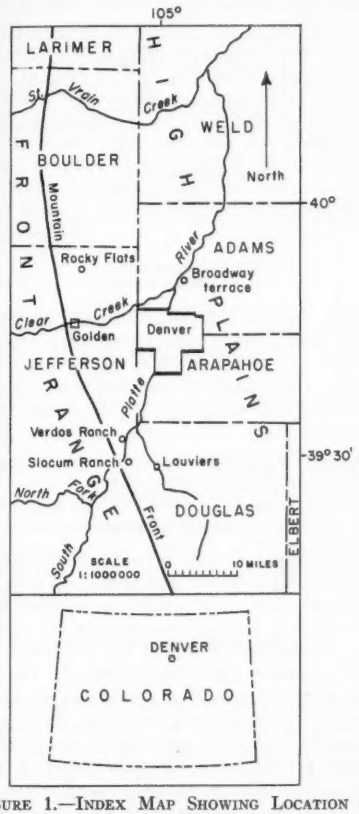

FIGURE 1.—INDEX MAP SHOWING LOCATION OF TYPE AREA AND TYPE LOCALITIES

Rocky Flats Alluvium

The oldest widespread Pleistocene alluvium recognized in the Denver area is here named the Rocky Flats alluvium, typically exposed in a gravel pit at the east edge of Rocky Flats in the NW¼SW¼ sec. 23, T. 2 S., R. 70 W., Golden quadrangle, Colorado. Here a sheet 10 to 40 feet thick of reddish-brown, poorly sorted, stony coarse sand unconformably overlies Mesozoic bedrock on a pediment about 1600 feet below the level of a subsummit surface (Rocky Mountain peneplain, Lee, 1917, p. 28; also called Bergen Park peneplain by Van Tuyl and Lovering, 1935) on the Front Range, and 100 feet above the next younger alluvium. The Rocky Flats alluvium is interpreted to be of Nebraskan or Aftonian age because of its relation to the next younger alluvium.

Verdos Alluvium

A second alluvial deposit, lying 100 feet below the Rocky Flats alluvium and 150 feet above the next younger alluvium, is here named the Verdos alluvium. The formation is typically exposed in an outcrop on the slope of a pediment on the Verdos Ranch in the NE¼NW¼SE¼

sec. 22, T. 6 S., R. 69 W., Littleton quadrangle, Colorado. Here a sheet of 16 to 35 feet of brown, well-stratified coarse sand containing some larger stones and a volcanic ash bed unconformably overlies Mesozoic bedrock. The Verdos alluvium is interpreted to be of Kansan or Yarmouth age on the basis of the volcanic ash, which is considered by Powers and others (1958, p. 1631) to be correlative with the Pearlette ash of Kansan or Yarmouth age (Frye and Leonard, 1952, p. 24, 104).

TABLE 1.—ALLUVIAL SEQUENCE EAST OF THE FRONT RANGE NEAR DENVER, COLORADO

System	Series	Stage or substage		Formation
QUATERNARY	Recent	Late		Post-Piney Creek alluvium
				Piney Creek alluvium
		Early		Pre-Piney Creek alluvium
	Pleistocene	Wisconsin	Late	Broadway* alluvium
			Early	Louviers* alluvium
		Illinoian or Sangamon		Slocum* alluvium
		Kansan or Yarmouth		Verdos* alluvium
		Nebraskan or Aftonian		Rocky Flats* alluvium

* New names

Slocum Alluvium

A third alluvial deposit that lies 150 feet below the Verdos alluvium and 100 feet above the modern streams is here named the Slocum alluvium. The type locality is an exposure along one face of a limestone quarry on the Slocum Ranch in the SW¼NW¼ sec. 35, T. 6 S., R. 69 W., Kassler quadrangle, Colorado. The alluvium consists of 10 to 90 feet of moderate reddish-brown, well-stratified, clayey coarse sand with lenticular beds of pebbles and silt. The Slocum alluvium is interpreted to be of Illinoian or Sangamon age because it is the youngest pre-Wisconsin alluvium. Its molluscan fauna is dominated by the warmth-loving forms *Pupilla blandi* Morse, *Pupoides hordaceus* (Gabb), *P. inornatus* Vanatta, and *Gastrocopta pellucida hordeacella* (Pilsbry).

Louviers Alluvium

The highest Wisconsin terrace in the area is underlain by a deposit here named the Louviers alluvium. The type locality is selected as a gravel pit at the northeast edge of the town of Louviers in the SW¼SE¼ sec. 33, T. 6 S., R. 68 W., Kassler quadrangle, Colorado. The terrace at the type locality lies 60 feet above the modern stream and 40 feet below the Slocum alluvium. The Louviers consists of a reddish-brown pebbly facies along the major streams and a yellowish-brown silty facies along the minor streams. It is interpreted to be of early Wisconsin age on the basis of fossil mammals and mollusks. The diagnostic mammals are *Bison antiquus* Leidy, *Mammuthus* (*Parelephas*) *columbi* (Falconer), and *Camelops* sp. *Vallonia*

cyclophorella Ancey, *V. gracilicosta* Reinhardt, cf. *Succinea avara* Say, *Pupilla muscorum* (Linné), *Hawaiia minuscula* (Binney), and *Lymnaea parva* Lea are the most common and characteristic species in a cold-loving molluscan suite.

Broadway Alluvium

The lowest Wisconsin terrace in the area—called the Broadway terrace by Hunt (1954, p. 104)—is underlain by alluvium of two ages. The lower part is cobbly Louviers alluvium partly eroded by the South Platte River and subsequently overlain by a sheet of later alluvium (Hunt, 1954, p. 104). This upper deposit is here named the Broadway alluvium, from Broadway Avenue on the Broadway terrace, which lies 25 feet above the South Platte River in Denver. The type locality is a gravel pit in the SE¼ sec. 30, T. 2 S., R. 67 W. Other nearby gravel pits also show typical sections of the Broadway alluvium. The Broadway alluvium consists of 12 to 15 feet of reddish-brown fine- to coarse-grained sand and some pebbles. Hunt (1954, p. 106) interpreted it to be of late Wisconsin age.

Recent Alluvium

Recent alluvium is subdivided into three deposits: pre-Piney Creek, Piney Creek, and post-Piney Creek alluvium. Pre-Piney Creek is composed of light-brown stratified silt, which forms terraces only in the smaller valleys. Piney Creek alluvium, composed of brownish-gray humic silt, sand, and clay, forms a flat-topped fill in almost every valley. Post-Piney Creek alluvium, a grayish-brown loose humic sand or silt, forms large terrace deposits only along the major streams, but forms a 3- to 6-inch mantle over Piney Creek alluvium in many small valleys.

Relation of Geomorphic Development to Alluvial Sequence

The alluvial sequence here described forms a geologic record of the physical processes—controlled by cyclic changes in climate—that were responsible for the geomorphic development of the area. Each alluvium represents part of a single climatic cycle that embraces five processes in chronologic order: (1) valley cutting, (2) pedimentation, (3) alluviation, (4) wind erosion and deposition, and (5) soil formation. At five times in the Pleistocene—because of a change in base level—streams cut downward. After each of the first three times of downcutting, the streams attained a profile of equilibrium and then cut sidewise to form pediments. In early Wisconsin time the streams again cut downward, deeper into bedrock than before or since. In late Wisconsin time valleys again were entrenched, but only a few feet into Louviers alluvium. Base level was not stable long enough in Wisconsin time to allow widespread pedimentation.

The overall result of the foregoing processes is a landscape marked by gently sloping surfaces at three topographic levels: (1) the high, poorly preserved pre-Pleistocene subsummit surface (an ancient pediment?) developed on the Precambrian rocks of the Front Range; (2) the intermediate three Pleistocene pediments developed on the sedimentary rocks at the mountain front; and (3) the low, well-preserved late Pleistocene fill terraces.

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SLIPS AND SEPARATIONS

BY VINCENT C. KELLEY

Abstract

Inasmuch as "left" and "right" pertain to lateral situations it is proposed that "lateral" be deleted from the compound adjectives employed in such terms as "right-lateral slip faults". Instead, the simpler and clearer expressions such as "left offset," "right wrenching," "left slip," "right separation," etc., are better. The terms "sinistral" or "dextral" may be substituted for "left" and "right," but the confusion currently taught that "sinistral" when applied refers to slip, whereas "left-lateral" refers to separation should be avoided.

In recent years, with the increasing recognition of the abundance of wrench faults and through the works of Gill (1941, p. 74–80), Anderson (1942; 1951), Hill (1947; 1959), Billings (1954), and Crowell (1959), the analogies between separations in plan and in section have been pointed out. Although the geometry of the displacements is identical in the two instances the considerations are different because the map is viewed from only one side (downward) and has no designation equivalent to the hanging wall. However, left and right groups of fault separations, in plan, are analogous to normal and reverse groups in cross section.

There is only a modicum of agreement in the standard works on what, for example, constitutes a normal fault. The AGI Glossary (American Geological Institute, 1957), Lindgren (1928, p. 160), and Bateman (1950, p. 336) specify that in a normal fault the hanging wall *has* moved down, whereas the Nevin (1949, p. 87), Leith (1923, p. 69), Lahee (1952, p. 220), Russell (1955, p. 114), and Billings (1954, p. 143) texts specify that the hanging wall *appears* to have moved down. There is also similar lack of agreement for the terminology of slips and separations in plan.

Dixon (p. 182) as early as 1921 appears to have been the first to use the terms "left" and "right" for displacements (heaves) or separations in plan; Gill (p. 79), in 1941, suggested "left" and "right" for strike *slip*; and Anderson (1942, p. 55; 1951, p. 19) proposed the terms sinistral and dextral for these two kinds of relative movements. In 1947 Hill (p. 1671) proposed the terms "left lateral" and "right lateral" for plan separations. In 1954 Billings (p. 144) followed both Anderson and Hill, and in using "left lateral" for direction of separation and "sinistral" for relative direction of slip he was consistent with his cross-section terminology, wherein "normal" was used for apparency of movement in a dip separation and "gravity" for slip direction. Many geologists, however (Crowell, 1959, p. 2673), object to the genetic connotation of the "gravity" term. Finally, Hill (1959, p. 221) has proposed a "dual" classification involving lateral and vertical aspects of separation and slip. In his proposal the term "left-lateral slip fault" is substituted for Anderson's and Billings' "sinistral fault." I believe that most American geologists would not prefer the "sinistral" and "dextral" terms,[1] and possibly some paleontologists might visualize coiling configurations for faults of these designations!

On the other hand, the term "left-lateral slip fault" is cumbersome and somewhat redundant on two counts. Furthermore, according to the meaning that one may be getting from the term, it might be hyphenated otherwise as "left-lateral-slip," left lateral-slip, or left-lateral slip-fault. With regard to redundancy it may be noted that "slip" is implied in "fault," and left is lateral unless lying on one's side! Some of the difficulty appears to lie in the effort to classify by prefixed compound adjectives kinds of faults when the things to be classified are the separations and slips. Reference to any dictionary will soon refresh one's memory that "left" and "lateral" both pertain to side situations. The useful, yet commonly neglected, classification of faults with regard to sideways slippage or separation may be simply handled by just "left" and "right" as Gill (p. 79–80) did partly in 1941. Let's not burden ourselves with having to know that "left-lateral" refers to separation

[1] These terms appear to be fairly well established in Great Britain, as may be observed in the recent articles by Williams (1958) and Bott (1959).

and "sinistral" to slip. Hill's "lateral" terms are undesirable in that most geologists when reading "left-lateral fault" alone do not know that it does not refer to slip.[2] It is important to keep our terminologies simple and readily understandable where at all possible.

The difficulties may be resolved by simply referring to left separations, left offsets, left movements, left slips, or left wrenching of faults and discontinuing the use of "lateral," "sinistral," etc. In Gill's (1941, p. 79) "left strike-slip fault" or Hill's (1959, p. 219) "left-lateral slip fault," both "strike" and "lateral" are unnecessary. Therefore, it is proposed that "*left-slip fault*" be substituted for "left-lateral slip fault." For displacements in plan "*left separation*" or "*left offset*" should be used and not "left-lateral fault" because faulting commonly gives rise to both left and right separations within short distances as the result of a single slip. However, despite the hint of foreboding in the expression "sinistral movement" there is no really valid objection to the use of "sinistral" for "left" if it be extended to separation as well as slip. The real objection for me lies in the dual terminology and the unnecessary usages of "lateral" and "strike" with left or right. On the other hand, if one follows Hill (1959, p. 219) in using "left-lateral slip," then to be consistent he should use "normal *vertical*-slip."

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[2] The current literature has numerous examples of misuse or misunderstanding of this distinction, *e.g.*, Kimura (1959, p. 225).

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